Heat transfer in a "tank in tank" combi store

Knudsen, Søren

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Søren Knudsen

Heat transfer in a ”tank in tank” combi store

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Preface

In this project theoretical investigations of a heat storage designed for a combi system are carried out. The investigated solar heating tank is a prototype from the Danish company Batec A/S.

The investigations, which are funded by the Danish Energy Agency, form part of the project "Danish-Swiss research cooperation on solar heating systems" file number 51181/99-0030, under the Danish Energy Agency's development programme for sustainable energy etc., UVE.

Project group:

Søren Knudsen, M.Sc. in Engineering, Ph.D. student
Simon Furbo, M.Sc. in Engineering, Ph.D.
Louise Jivan Shah, M.Sc. in Engineering, Ph.D.
Michael Ramskov, designer
Anne Rasmussen, correspondent

Summary

Theoretical investigations of a heat storage for a solar combi system have been carried out. The investigated combi store is manufactured by the Danish company Batec A/S. The theoretical investigations are carried out by means of a Computational Fluid Dynamics (CFD) program. The CFD program CFX 5.4 is used.

The combi store is a “Tank in Tank” storage where the domestic hot-water (DHW) tank is built in the space heating storage tank. The space heating storage tank is heated by the solar heat through a heat exchanger spiral in the bottom part of the tank. The heat is transferred from the space heating storage tank to the DHW tank through the tank wall of the DHW tank. If the required temperature level cannot be reached by means of the solar heat, the upper part of the storage tank can be heated by an auxiliary boiler.

A model of the combi store from Batec A/S has been built up in the CFD program. The model contains some simplifications to make the modelling and the simulation by CFD easier. The heat exchanger spiral in the bottom part of the space heating storage tank is not included in the CFD model, which means that only periods when the solar collector loop is not in operation can be simulated. Furthermore the domestic hot water is not included in the CFD model. Instead the tank wall of the DHW tank has a constant temperature during the simulation and by this the heat transfer from the space heating storage tank to the DHW tank can be calculated.

The fluid motion and the thermal conditions in the combi store have been investigated during 7 different operation situations.

For the 7 operation conditions the fluid motion around the inlets from and the outlets to the auxiliary power supply and from the space-heating loop have been investigated, respectively. It has been analysed how the thermal stratification in the space-heating storage tank is influenced by especially the inlet from the space-heating loop.

The heat transfer rate transferred to the domestic hot water has been calculated for the 7 operation conditions. Moreover, the convective heat transfer coefficient for the outside of the DHW tank wall has been calculated as a function of the height of the tank for each of the operation conditions.

1. Introduction

This report describes the theoretical investigations of a heat storage for a solar combi system. The investigated combi store is manufactured by the Danish company Batec A/S. The combi store has also been investigated experimentally at BYG.DTU in the report: Undersøgelse af et solvarmeanlæg til kombineret rum- og brugsvandsopvarmning, [1].

The purpose of the theoretical investigations is to investigate the fluid motion and the thermal conditions during typical operation conditions.

The theoretical investigations are carried out by means of a Computational Fluid Dynamics (CFD) program. A CFD program is a program that can provide numerical solutions of the governing equations for fluid and gas flows and for heat transfer. The advantage of a CFD program is that it is possible to get very detailed information about the fluid motion and the thermal conditions. The applied CFD program is CFX 5.4, [2].

The report is built as follows:

- in chapter 2 the CFD model of the combi store is described.
- in chapter 3 the calculated results are analysed and discussed.
- in chapter 4 the reached conclusions are given.

2. CFD model of combi store from Batec A/S

A model of the combi store from Batec has been built in CFX. In this chapter it will be described how the combi store is built up in CFX and at the same time the assumptions and simplifications made in connection with the building will be explained.

2.1 Specification of a CFD model

The combi store from Batec A/S is a so-called “Tank in Tank” storage. The domestic hot water is a tank inside a tank without pressure, containing water for space heating. Figure 1 shows a sketch of the combi store.

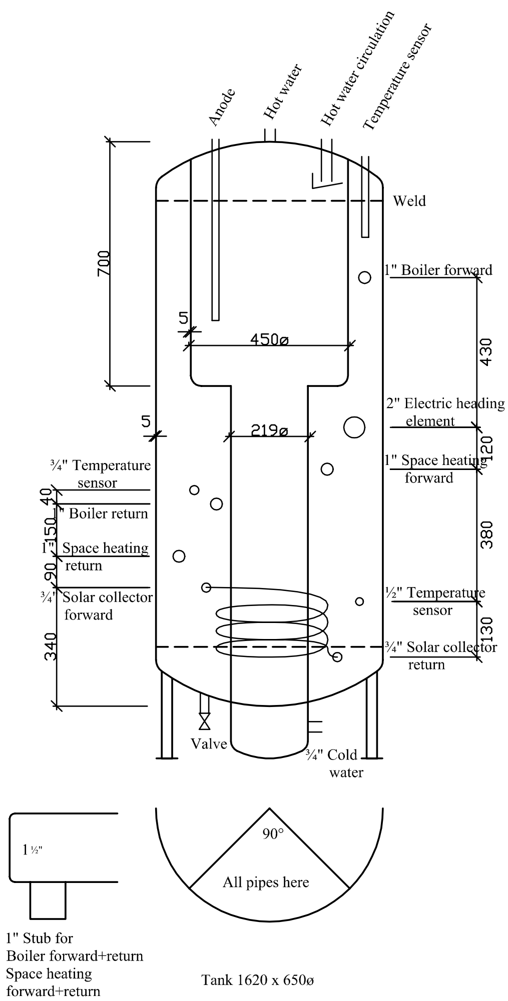

Figure 1: Sketch of the combi store from Batec A/S. The inner tank is for domestic hot water, whereas the outer tank is for water for space heating.

The calculation time when using CFD programs can be rather long, especially if the models are very complicated. Further, the combi store from Batec has some details that can make CFD modelling still more complicated. There are large dimension disparities between e.g. the diameter of the boiler inlet and the height of the tank. Also, there are large dimension disparities between the wall thickness and the height of the tank. Further, the twisted heat exchanger spiral is complicated to model and there are large dimension disparities between the diameter of the heat exchanger pipe and the height of the tank as well.

Therefore a number of simplifications have been made so that in CFX the final model of the combi store is somewhat simpler than the real combi store. Firstly, the heat exchanger spiral for solar energy is omitted, which means that only periods when the solar collector is not in operation are simulated. Secondly, the inner tank, the one with the domestic hot water, is omitted from the model. That is, it is not calculated how different operation conditions influence the thermal stratification in the domestic-water section of the tank. By the way, this would be interesting to investigate, but the model would be too comprehensive if it should be investigated in this project. Finally, also the tank material has been omitted from the model. This means that the heat transfer in the tank material is not simulated. Downward heat transfer can have a great effect on the thermal stratification, both in the domestic water section and in the space heating section, but this will not be investigated in the present project.

The above means that the model only contains the water in the tank with the space heating section, so with the built model it is only possible to investigate what happens in the tank with water for space heating. With the model it is possible to investigate how the flows influence the thermal stratification at the inlet and the outlet, and how the heat transfer into the domestic water will be during different operation conditions. Further, it is possible to investigate the natural convection in the tank with water for space heating.

The model of the combi store in CFX is shown in Figure 2 at a vertical and a horizontal section, respectively.

Table 1 shows the distance from the bottom to the inlets and outlets. The stated inlets and outlets are 1” pipe stubs. Table 2 shows the volume of space heating and domestic water in the combi store, respectively.

Type	**Distance from the bottom of the tank [m]**
Inlet from boiler loop	1.23
Outlet to boiler loop	0.58
Inlet from space-heating loop	0.43
Outlet to space-heating loop	0.68

Table 1: Specification of the locations of inlets and outlets for the combi store.

	Volume [l]
Domestic water	155
Water for space heating	385
Total	540

Table 2: The volume of domestic water and water for space heating in the tank, respectively.

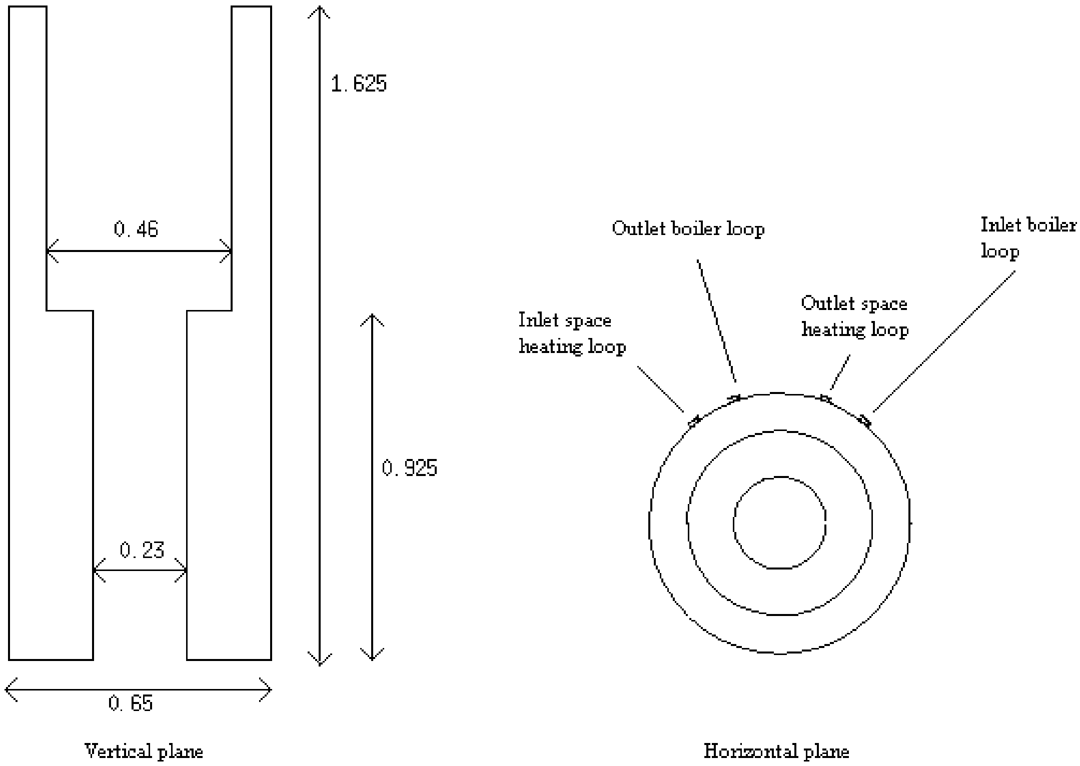

Figure 2: Vertical and horizontal section of the model in CFX. The units of measurement are in metres.

At simulations with the model in CFX, a laminar calculation model is used. This is a simplification compared with reality, too, as in most cases there will be turbulence around inlets. The laminar calculation model has a considerably shorter calculation time than a turbulent calculation model, which is the reason why the laminar calculation model is used. The turbulence limited to a very small part of the tank so therefore it is estimated that the laminar model can be used.

Natural convection, which is caused by differences in density, can be calculated in several ways. In this case in CFX, the natural convection is calculated by Boussinesq's buoyancy approximation, which is good at simulating flows caused by comparatively small temperature differences [2, 3]. Boussinesq's buoyancy approximation calculates the differences in density by the following equation:

$$\Delta\rho = \rho \cdot \beta \cdot \left(T - T_{ref}\right) \qquad (1)$$

where

T	variable temperature	[K]
T_{ref}	reference temperature	[K]
β	thermal expansion coefficient	[K^{-1}]
ρ	density at the reference temperature	[kg/m^3]
$\Delta\rho$	difference in density (difference from reference condition)	[kg/m^3]

This temperature dependence of the density thus forms part of the solution of Navier-Stoke's equations, whereas all other physical properties are assumed to be constant.

In CFX the calculations are carried out with a time step of one second.

2.1.1 Grid distribution of model

In CFX the model of the combi store is divided into a computational mesh composed of small cells. The computational mesh consists of prisms close to the tank walls, whereas it consists of tetrahedrals in the rest of the model. This means that the computational mesh is finer close to the tank walls, where large variations of flow and temperature may occur, and that it is coarser in the rest of the tank. Table 3 shows the number of computational cells in the model in CFX. Figure 3 shows the computational mesh at a vertical section in the tank, whereas Figure 4 shows the computational mesh at horizontal sections in the tank on a level with inlet from boiler loop and outlet to boiler loop, respectively.

Tetrahedrals	51362
Prisms	55428
Total number of cells	106790

Table 3: Number of cells in the model in CFX.

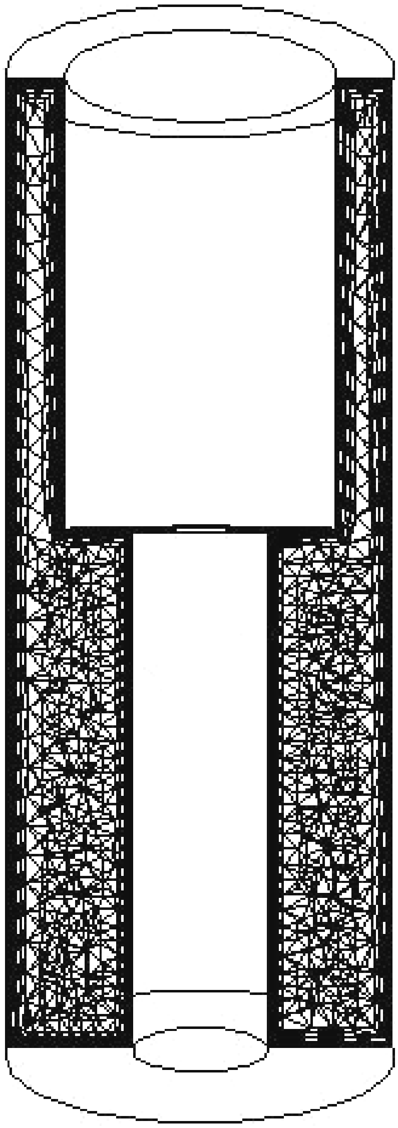

Figure 3: The computational mesh at a vertical section in the tank.

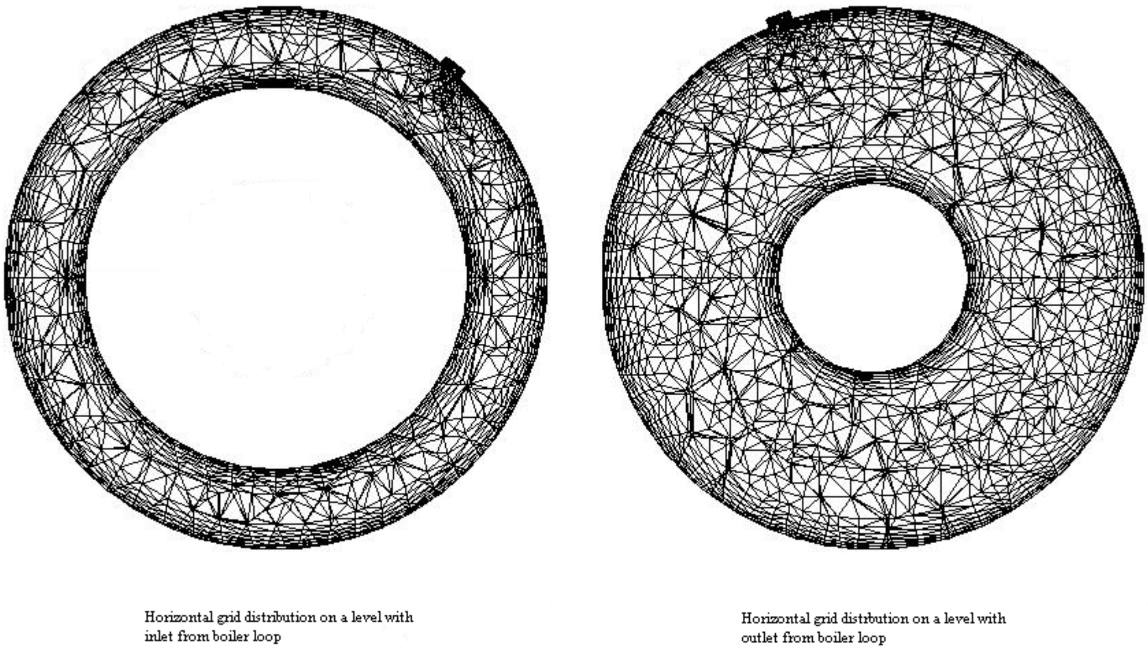

Figure 4: Computational mesh at a horizontal section on a level with inlet from boiler loop (left) and outlet to boiler loop (right), respectively.

2.1.2 Boundary conditions

A number of boundary conditions are to be set in the model. These boundary conditions vary from operation condition to operation condition, however, but the principle in them will be described below, and the exact values will be specified in the description of each operation condition.

Boundary conditions are to be set for the tank walls, and that applies to the walls of the hot-water tank as well as the tank wall. Further, the boundary conditions are to be stated for inlet and outlet, respectively.

The boundary conditions for the walls are divided in such a way that different types of boundary conditions are set for the walls against the domestic water and the walls towards the surroundings, respectively. For the walls against the domestic water, a temperature is stated that will be fixed for the whole simulation. This fixed temperature can vary with the height of the wall. The fixed temperature of the wall against the domestic water makes it possible - under the stated conditions – to calculate the size of the heat flow and the thermal transmittance from the water in the space heating storage tank to the wall of the hot-water tank.

For the walls against the open, a heat flow from the water in the space heating storage tank and against the open is stated. This heat flow is calculated from the temperature of the water in the space heating storage tank, the ambient temperature, and the heat loss coefficient of the tank. The ambient temperature is set to 20ºC in all cases. Table 4 shows the calculated heat loss coefficient for the top, sides, and bottom of the tank, respectively. The top and the sides are insulated with a 100 mm foam mat with a thermal conductivity of 0.045 W/m·K. There is no insulation at the bottom of the tank.

Part of the tank	Heat loss coefficient [W/K]
Top	0.2
Bottom	2.5
Sides	1.7
Total	4.4

Table 4: Calculated heat loss coefficients for tank.

The inlet from boiler loop and space-heating loop, respectively, are to be stated by means of a mass flow rate and a temperature of the incoming water. The outlet to the space-heating loop is stated by a mass flow rate, corresponding to the mass flow rate defined by the inlet from the space-heating loop. The temperature of the outflowing water is not to be stated, as this is calculated by CFX. The outlet to the boiler loop is defined as an ”opening”, which means that by the continuity equation CFX calculates the mass flow rate in such a way that just as much water flows out of the tank as into it. The advantage of using ”opening” is that the program can make allowance for possible recirculation close to the outlet. This is specified in [2].

The temperature of the water in the space heating storage tank at the beginning of the calculations is to be stated. The temperature is given as a function of the tank height so that there is a realistic thermal stratification in the space heating storage tank at the beginning of the calculations. From the beginning, horizontal thermal stratification is not considered.

2.1.3 Calculation of convective heat transfer coefficient for the outside of the hot-water tank

CFX calculates the heat flux [W/m²] between the water in the space heating storage tank and the tank wall against the domestic water in different heights in the tank. The convective heat transfer coefficient between the water in thespace heating storage tank and tank wall against domestic water is calculated by the following equation:

$$h_{c,z} = \frac{q_{w,z}}{T_{f,z} - T_{w,z}} \qquad (2)$$

where:

$h_{c,z}$	is the convective heat transfer coefficient in the height ”z”	[W/m²·K]
$q_{w,z}$	is the heat flux in the height ”z”	[W/m²]
$T_{f,z}$	is the mean temperature of the space heating water in the height ”z”	[K]
$T_{w,z}$	is the temperature of the tank wall against the domestic water in the height ”z”	[K]

2.2 Typical operation conditions

Two different typical conditions have been investigated. In the first condition (operation condition 1) a large quantity of domestic hot water has just been tapped, so that the domestic water has become cold, whereas the water for space heating is still comparatively warm. In the other condition (operation condition 2) both domestic water and water for space heating is heated. For both of these main conditions simulations have been carried out with different operations of boiler loop and space-heating loop, respectively, so that a total of 7 different operation conditions have been simulated. For each of the given operation conditions, simulations have been carried out corresponding to 10 minutes' operation.

2.2.1 Condition 1

Condition 1 corresponds to a condition where a large quantity of domestic hot water has just been tapped. This condition is divided into 3 operation conditions (operation conditions 1a, 1b and 1c) with different operations of boiler loop and space-heating loop. Figure 5 shows temperature profiles for the hot-water tank wall and for the water in the space heating part, respectively. The temperature profile for the tank wall is kept during the whole simulation, whereas the temperature profile for the space heating water is only an initial profile.

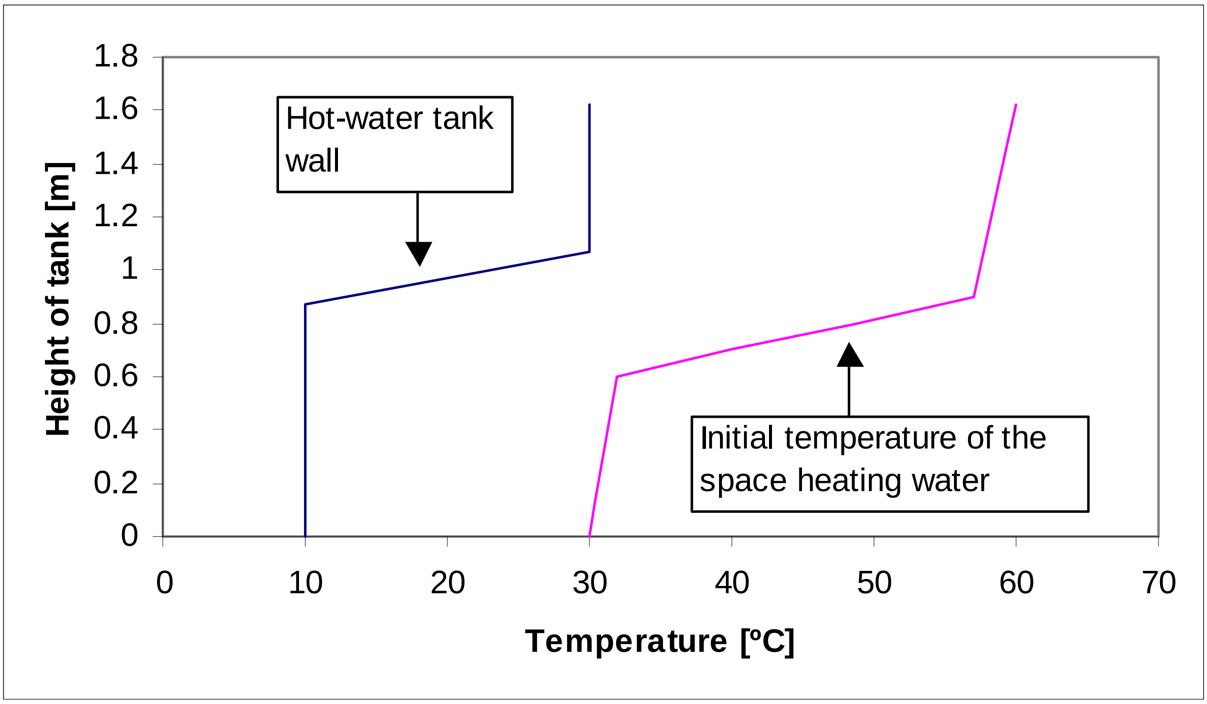

Figure 5: Initial temperature profiles for operation condition 1.

Operation condition 1a:

The boiler loop is operating with a volume flow rate of 10 l/min and an inlet temperature to the tank of 65ºC. The space-heating loop is not in operation.

Operation condition 1b:

The boiler loop is operating with a volume flow rate of 10 l/min and an inlet temperature to the tank of 65ºC. The space-heating loop is operating with a volume flow rate of 0.7 l/min and an outlet temperature to the tank of 20.5ºC.

Operation condition 1c:

The boiler loop is operating with a volume flow rate of 10 l/min and an inlet temperature to the tank of 65ºC. The space-heating loop is operating with a volume flow rate of 1.4 l/min and an outlet temperature to the tank of 20.5ºC.

2.2.2 Condition 2

Condition 2 corresponds to a condition where both domestic water and space heating water is heated. This condition is divided into 4 operation conditions (operation conditions 2a, 2b, 2c and 2d) with different operations of boiler loop and space-heating loop. Figure 6 shows temperature profiles for the hot-water tank wall and for the water in the space heating part. The temperature profile for the tank wall is kept during the whole simulation, whereas the temperature profile for the space heating water is just an initial profile.

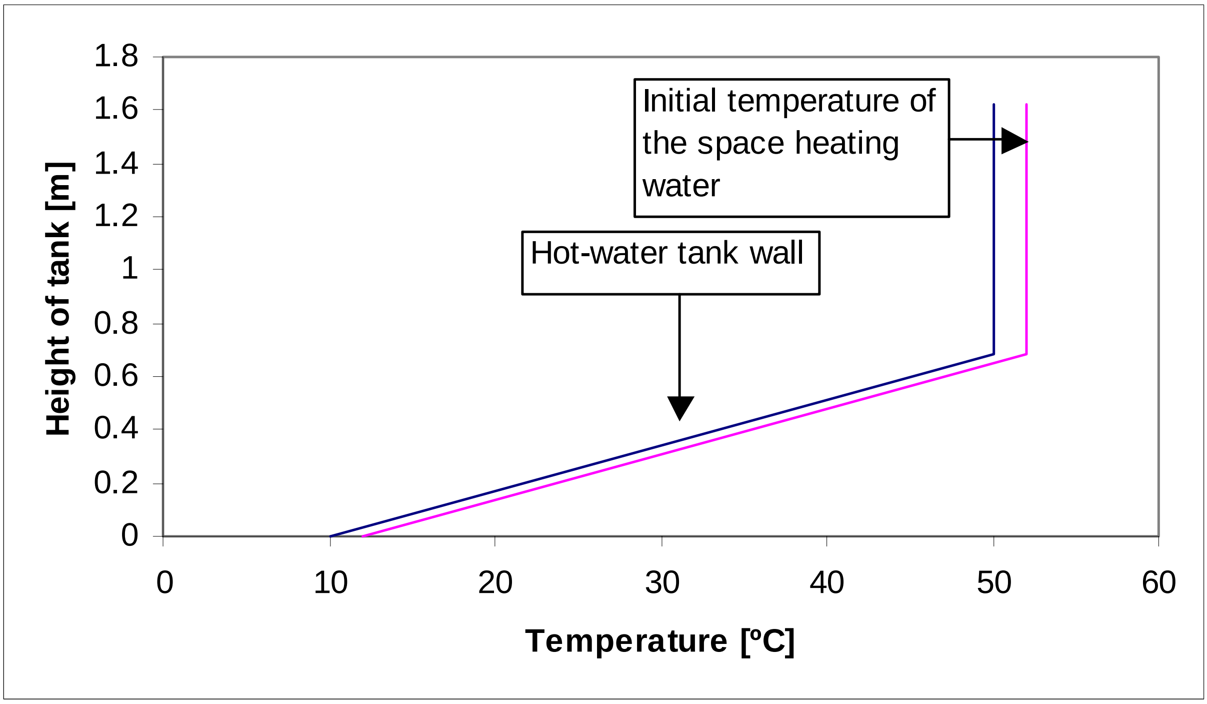

Figure 6: Initial temperature profiles for operation condition 2.

<u>Operation condition 2a:</u>
The boiler loop is operating with a volume flow rate of 10 l/min and an inlet temperature to the tank of 65ºC. The space-heating loop is not in operation.

<u>Operation condition 2b:</u>
The boiler loop is operating with a volume flow rate of 10 l/min and an inlet temperature to the tank of 65ºC. The space-heating loop is operating with a volume flow rate of 1.4 l/min and an outlet temperature to the tank of 20.5ºC.

<u>Operation condition 2c:</u>
The boiler loop is not in operation. The space-heating loop is operating with a volume flow rate of 1.4 l/min and an outlet temperature to the tank of 20.5ºC.

<u>Operation condition 2d:</u>
The boiler loop is not in operation. The space-heating loop is operating with a volume flow rate of 1.4 l/min and an outlet temperature to the tank of 30ºC.

2.2.3 Outline of operation conditions

Table 5 shows an outline of he 7 operation conditions.

Operation condition	**Boiler loop**				**Space-heating loop**			
	Flow [l/min]	Inlet temperature [ºC]	Inlet velocity [m/s]	Re_{inlet} [-]	Flow [l/min]	Inlet temperature [ºC]	Inlet velocity [m/s]	Re_{inlet} [-]
1a	10	65	0.24	14923	-	-	-	-
1b	10	65	0.24	14923	0.7	20.5	0.017	481
1c	10	65	0.24	14923	1.4	20.5	0.033	961
2a	10	65	0.24	14923	-	-	-	-
2b	10	65	0.24	14923	1.4	20.5	0.033	961
2c	-	-	-	-	1.4	20.5	0.033	961
2d	-	-	-	-	1.4	30	0.033	1132

Table 5: Outline of key figures for the 7 operation conditions.

3. Results of CFD-calculations

A number of simulations have been carried out with the built CFD-model of the combi store from Batec A/S. The object of the simulations is to investigate the fluid motion and heat transfer in the tank during a number of typical operation conditions.

To begin with, each of the 7 operation conditions are investigated separately, and then the results of the different operation conditions are compared. During each operation condition, the development of the thermal stratification in the space heating storage tank and the development of the inlet and outlet temperatures to the space heating storage tank are investigated. In addition, investigations are made of the temperatures and fluid motion around inlet and outlet at the end of the simulation. Finally, the convective heat transfer coefficient and the heat transfer between the space heating water and hot-water tank wall are investigated.

3.1 Operation condition 1a

At the operation condition 1a the starting temperatures stated in Figure 5 are used, and the boiler is operating with a flow of 10 l/min and an inlet temperature to the space heating storage tank of 65ºC. The space-heating loop is not in operation.

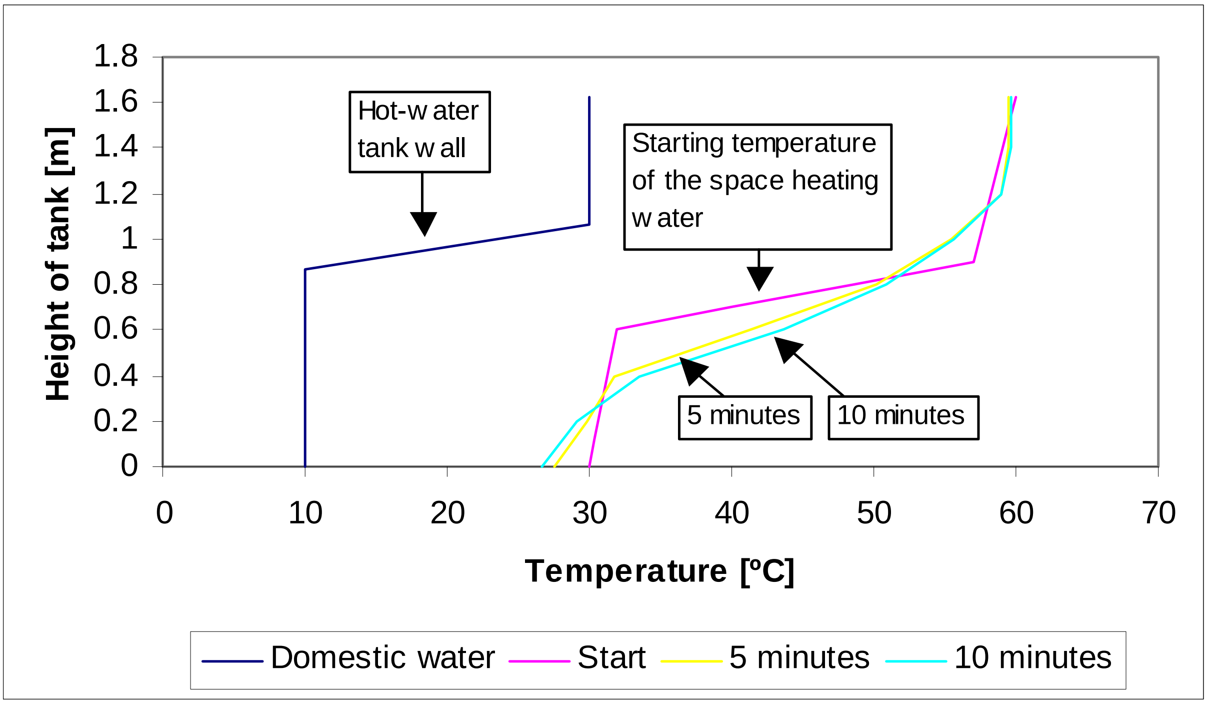

Figure 7: Calculated temperatures in the space heating storage tank at the start, after 5 minutes, and after 10 minutes at operation condition 1a.

Figure 7 shows the thermal stratification in the space heating storage tank at the beginning of the simulation, after 5 minutes, and after 10 minutes. The temperatures after 5 minutes and 10 minutes, respectively, are weighted mean temperatures at each height level, as horizontal thermal stratification occurs at simulations. It appears from Figure 7 that the largest part of the energy supply from the boiler loop goes to heating up the middle part of the space heating water. At the same time the greatest change takes place from the start to the 5th minute, whereas there is no particular change from the 5th to the 10th minute. The reason why the greatest change in the temperature profile takes place at the start is that the temperature of the hot-water tank wall is constant during the simulation, and after simulation of 5 minutes' operation the induced power from the boiler loop starts to correspond to the power that is emitted to the hot-water tank wall and to the heat loss. Further, it appears that the temperature at the top of the space heating storage tank does not get higher than 60ºC in spite of the fact that the inlet temperature from the boiler loop is 65ºC.

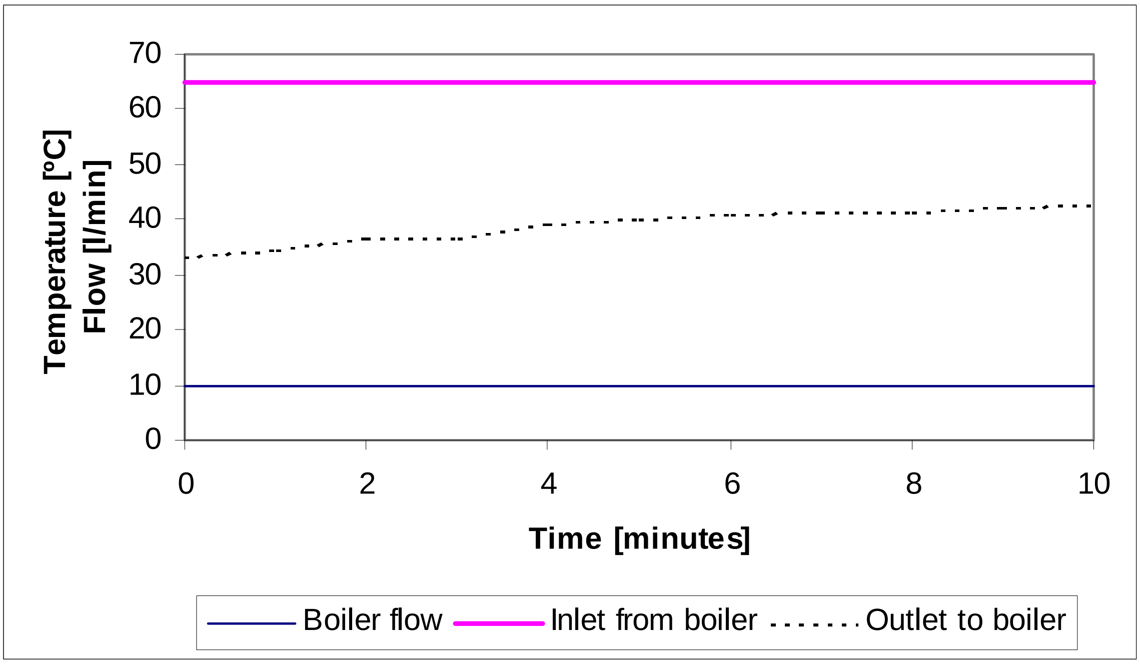

Figure 8: Inlet and outlet temperatures from the boiler loop and flow in the boiler loop as a function of the time for operation condition 1a. The induced power from the boiler loop is 16 kW after 10 minutes in operation.

Figure 8 shows the calculated temperatures for inlet and outlet of the boiler loop and the flow in the boiler loop as a function of the time. It appears that the inlet temperature from the boiler loop to the space heating storage tank and the flow in the boiler loop are constant at 65ºC and 10 l/min, respectively. The outlet temperature from the space heating storage tank to the boiler loop rises from 33ºC to 43ºC as a consequence of the heating of the middle part of the tank of the boiler loop. The induced power from the boiler loop falls during the 10 minutes' operation from 22 kW to 16 kW.

3.1.1 Temperature and fluid motion around inlet and outlet

Figure 9 shows the temperature of the space heating water in a horizontal section on a level with the inlet from the boiler loop (1.23 m from the bottom of the tank). It appears that the hot water from the boiler loop enters the tank and spreads round the tank wall into the domestic water.

Figure 10 and Figure 11 show the flows in a horizontal section on a level with the inlet from the boiler loop. It appears from Figure 10 (the size of the vectors indicates the velocity of the flow), that the flow is very strong just around the inlet and that the inlet flow hits the tank wall against the domestic water and then flows round along the tank wall. A touch of a minor recirculation is also seen on each side of the inlet flow. The rest of the flows are very small.

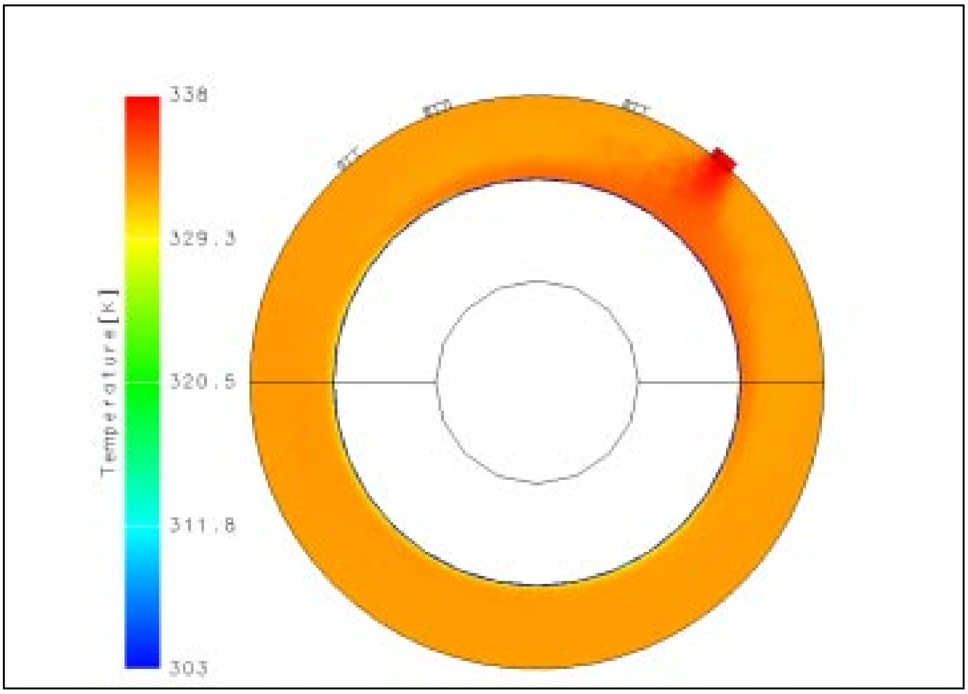

Figure 9: Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the boiler loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

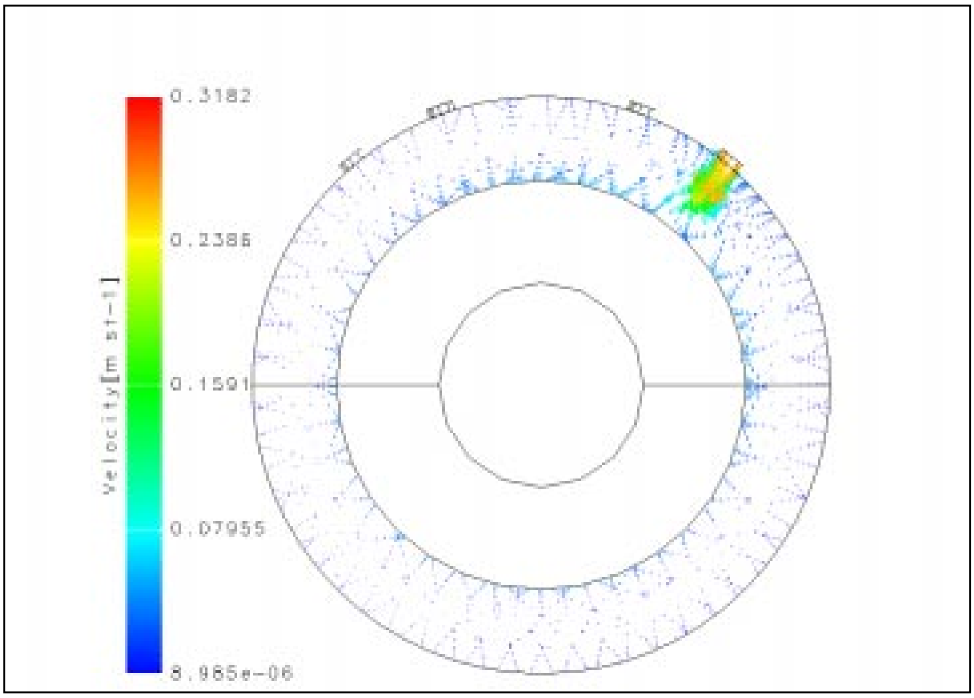

Figure 10: Velocity vectors in a horizontal section on a level with the inlet from the boiler loop. The range of colours indicates the velocity in [m/s].

In Figure 11 there is no connection between the size of the vectors and the velocity rate, the vectors only indicate the direction of the flows. The velocity of the flow is indicated by the range of colours. Here it appears more clearly that the flow enters and hits the tank wall against the domestic water and then the water flows round closely along the tank wall. The recirculation on each side of the inlet flow can also be seen clearer in this figure. Further, it appears that the flow is not completely symmetrical around the tank wall against the domestic water. This is due to the fact that the outlet to the boiler loop is turned 60º to the inlet from the boiler loop.

Figure 12 shows the flow in a vertical section on a level with the inlet from the boiler loop. As also appears from Figure 10 and Figure 11, the water from the inlet flows in horizontally and hits the tank wall against the domestic water. From here some of the water flows down along the tank wall and most likely down towards the outlet to the boiler loop, while some flows up along the tank wall towards the top of the tank. There is a downward flow along the tank wall against the domestic water in the side opposite the inlet from the boiler loop.

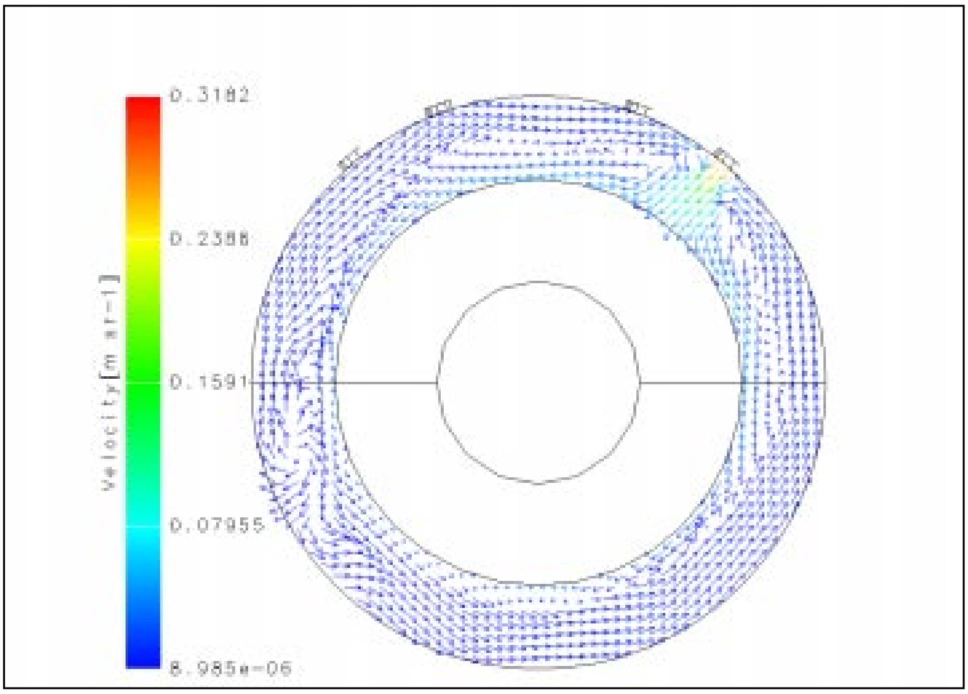

Figure 11: Vectors showing the flow in a horizontal section on a level with the inlet from the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

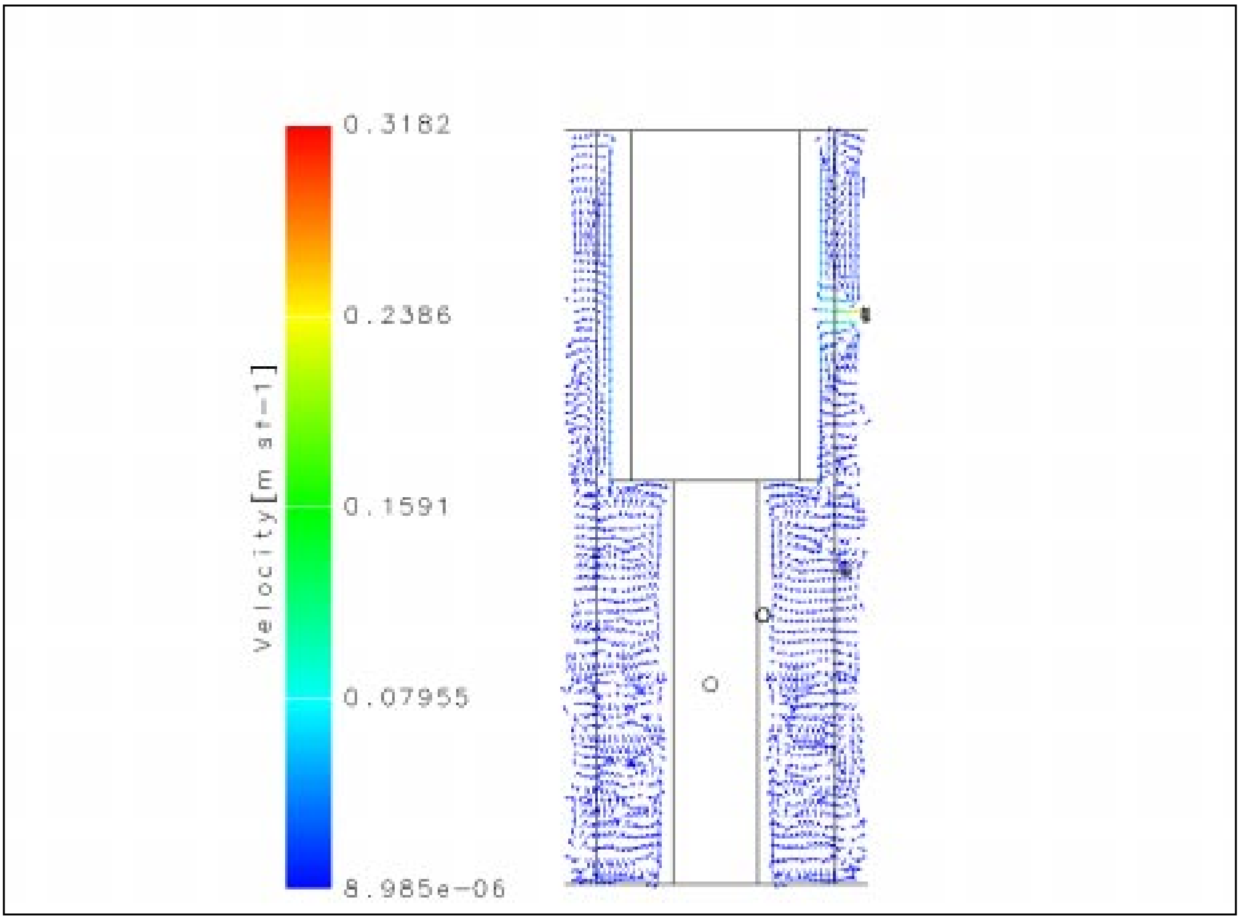

Figure 12: Vectors showing the flow in a vertical section on a level with the inlet from the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

Figure 13 shows the temperature of the space heating water in a vertical section on a level with the outlet to the boiler loop (0.58 m from the bottom of the tank). It appears that the temperature is constant on this level apart from the boundary layer close to the tank wall against domestic water where the temperature is a little lower.

Figure 14 and Figure 15 show the flows in a horizontal section on a level with the outlet to the boiler loop. Figure 14 shows the flows where the size of the vectors depends on the flow rate, and from this it appears that it is only close to the outlet that the flows have a certain volume. The rest of the flows are very small. Figure 15 shows the direction of the flows (the size of the vectors does not show anything about the velocity) and most of the flow on the horizontal level have turned towards the outlet.

Figure 16 shows the flows in a vertical section on a level with the outlet to the boiler loop. It appears that the outlet only affects the flows close to the outlet. The rest of the flows are very small.

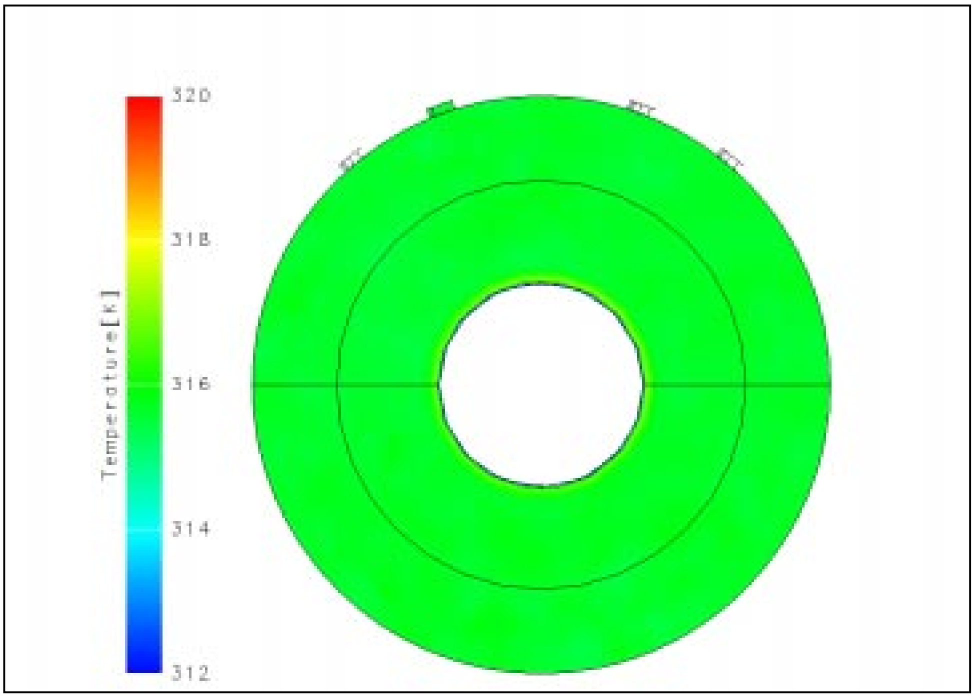

Figure 13:Calculated temperatures of the space heating water at a horizontal section on a level with the outlet to the boiler loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

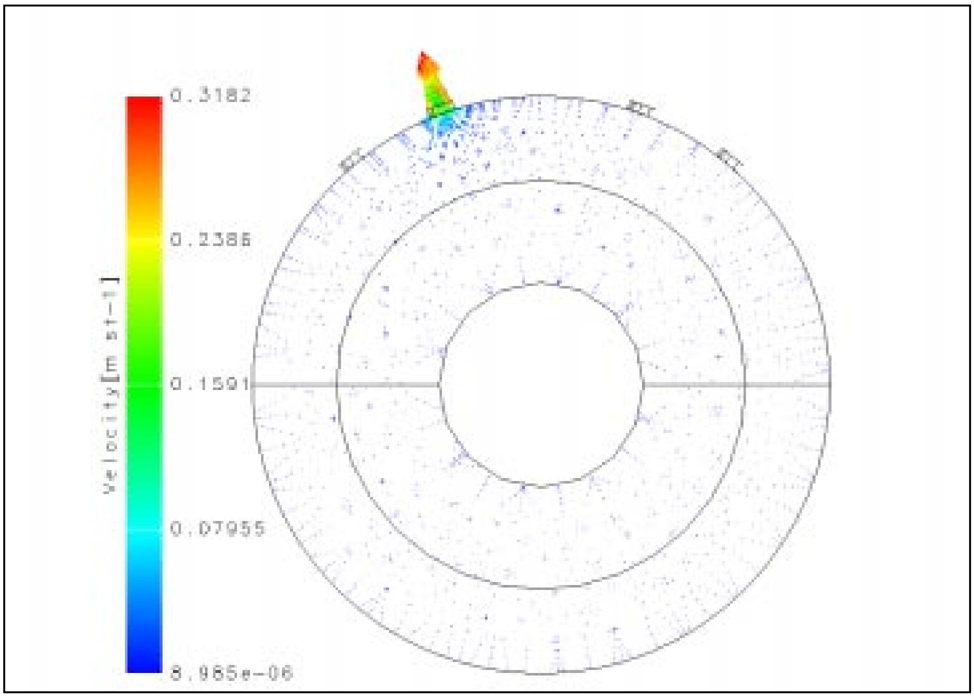

Figure 14: Velocity vectors in a horizontal section on a level with the outlet to the boiler loop. The range of colours indicates the velocity in [m/s].

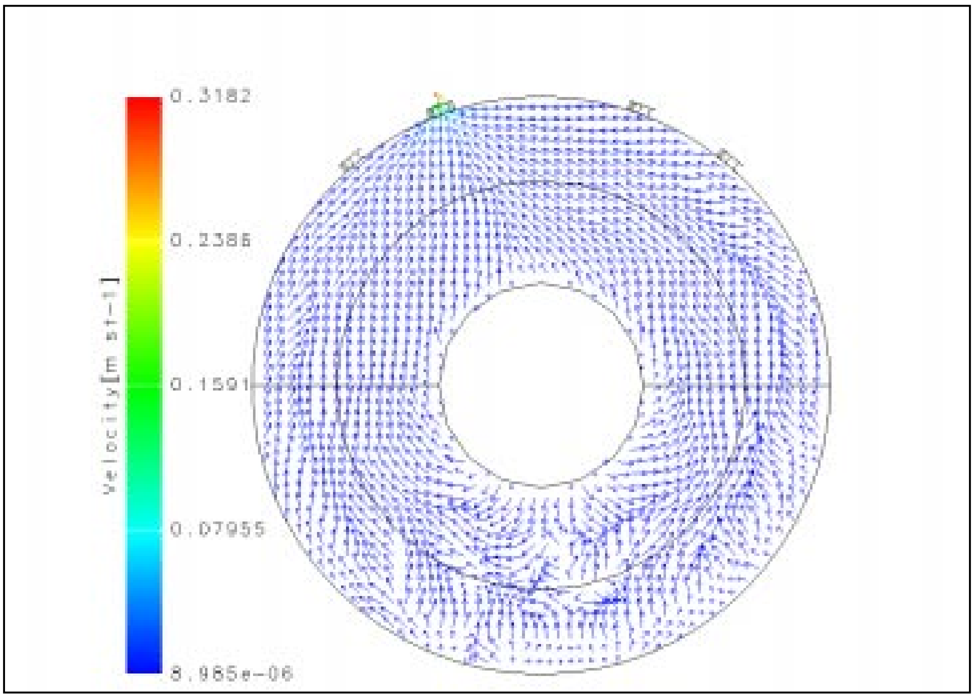

Figure 15: Vectors showing the flow in a horizontal section on a level with the outlet to the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

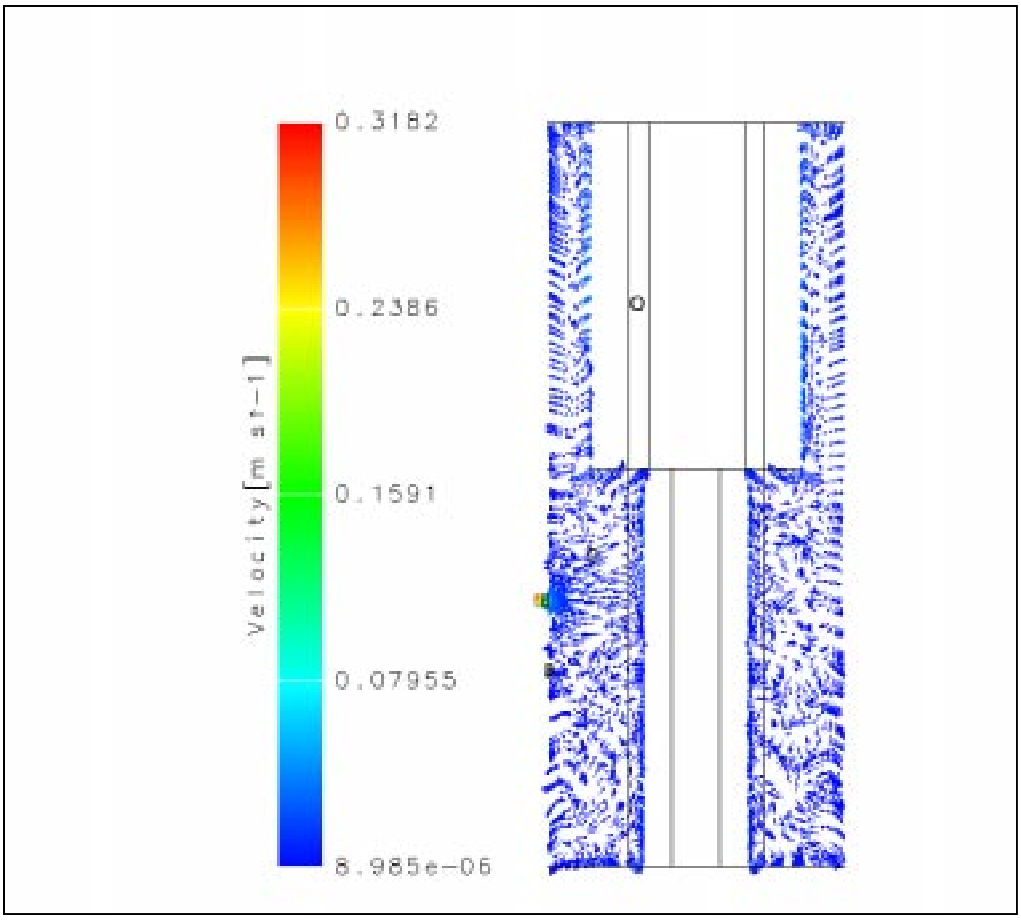

Figure 16: Vectors showing the flow in a vertical section on a level with the outlet to the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.1.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between the water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between the water in the space heating storage tank and the tank wall against the domestic water (i.e. the outside of the hot-water tank) is calculated by equation (2).

Figure 17 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux in Figure 17 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that the heat flux is largest on the middle part of the tank wall, i.e. just above the outlet to the boiler loop. There are two reasons for this, one is that the largest temperature difference between space heating water and tank wall against domestic water occurs at this level. The other reason is that there is a good downward flow close to the tank wall against the domestic water as the water flows down towards the outlet to the boiler loop. At this operation condition the total induced power from the space heating storage tank to the hot-water tank is 7.1 kW/m² corresponding to 13 kW.

Figure 18 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 210 W/m²·K and 270 W/m²·K. The average and total convective heat transfer coefficient, respectively, have been calculated to be 239 W/m²·K and 440 W/K, respectively, at this operation condition.

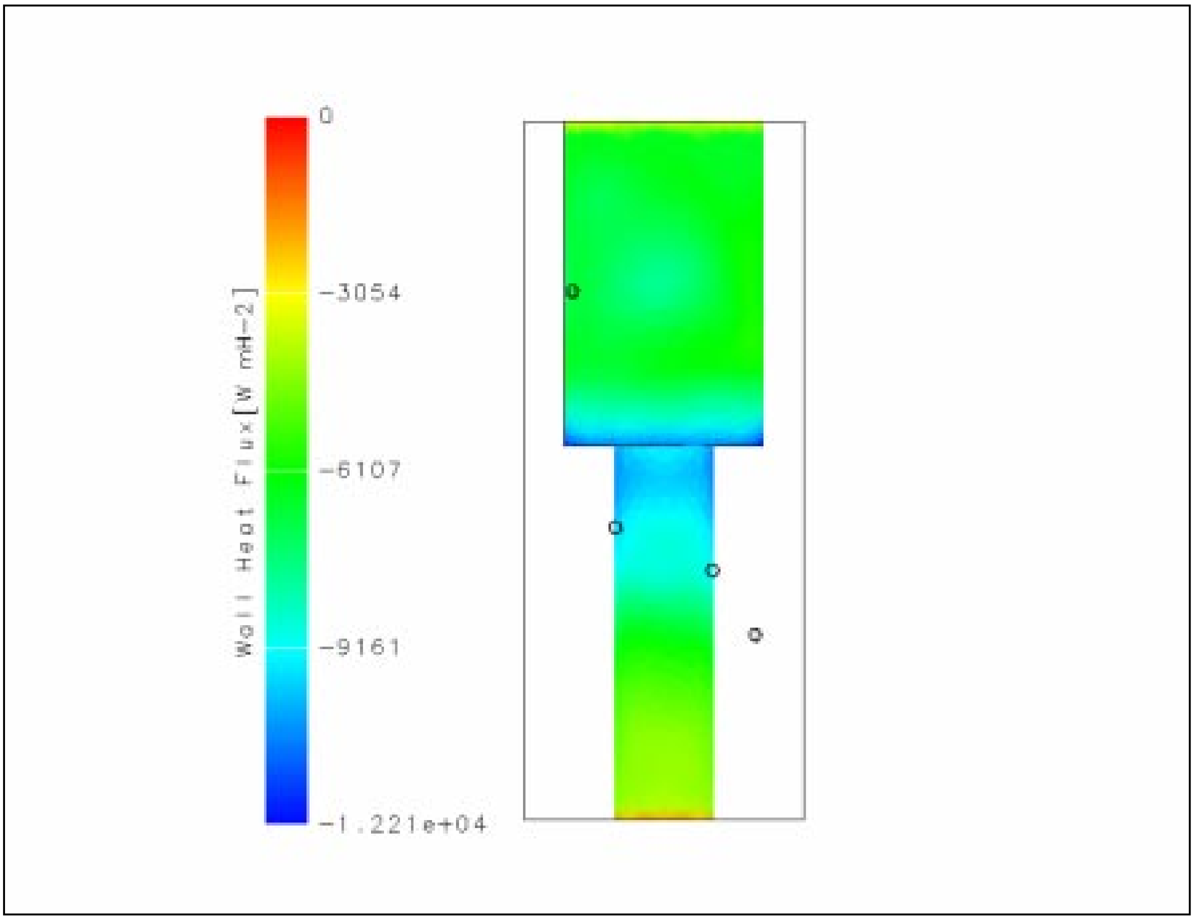

Figure 17: The calculated heat flux between the space heating water and the outside of the hot-water tank at operation condition 1a. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

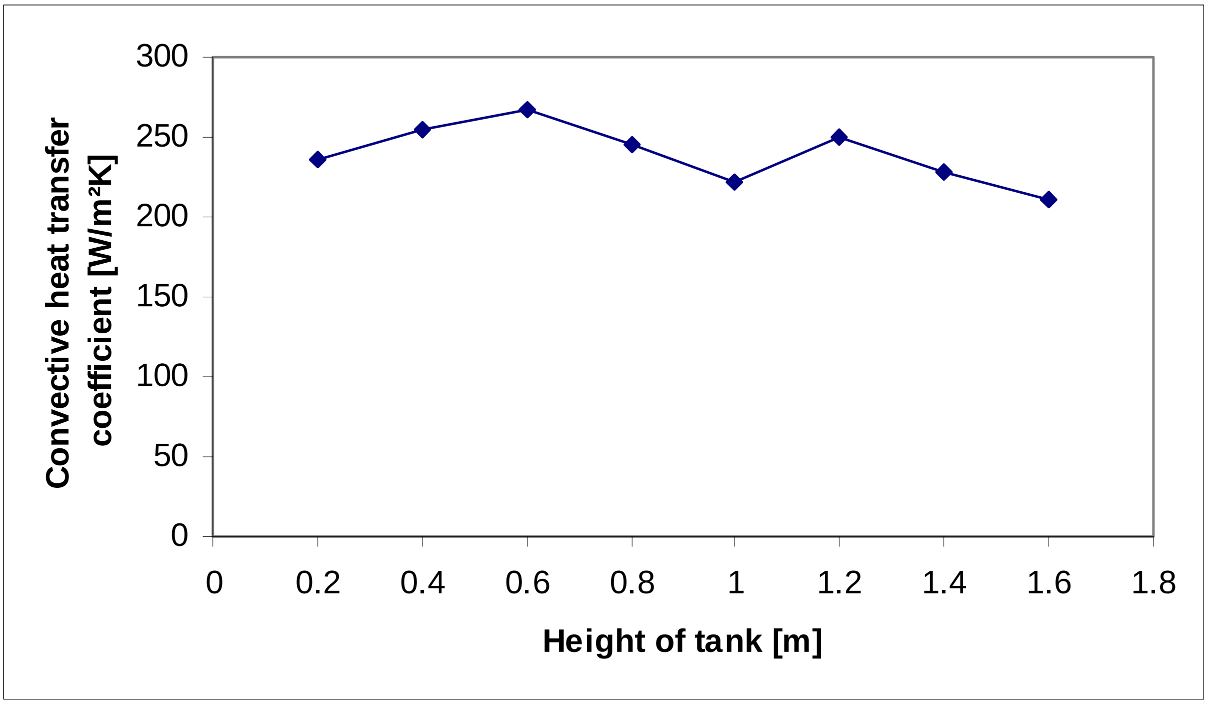

Figure 18: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 1a as a function of the height. The convective heat transfer coefficient has been calculated by equation (2).

3.2 Operation condition 1b

At operation condition 1b starting temperatures indicated in Figure 5are used. The boiler is in operation with a flow of 10 l/min and an inlet temperature to the space heating storage tank of 65ºC. The space-heating loop is in operation with a flow of 0.7 l/min and an outlet temperature to the space heating storage tank of 20.5ºC.

Figure 19 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears from Figure 19 that most of the energy supply from the boiler loop is used for heating up the middle part of the space heating water. At the same time the largest change is from start to the 5th minute, whereas there is no particular change from the 5th minute to the 10th minute. Further it appears that the temperature at the top of the space heating storage tank does not exceed 60ºC although the inlet temperature from the boiler loop is 65ºC. At the same time it appears that the space-heating loop, which is in operation unlike operation condition 1a, does not influence the thermal stratification very much.

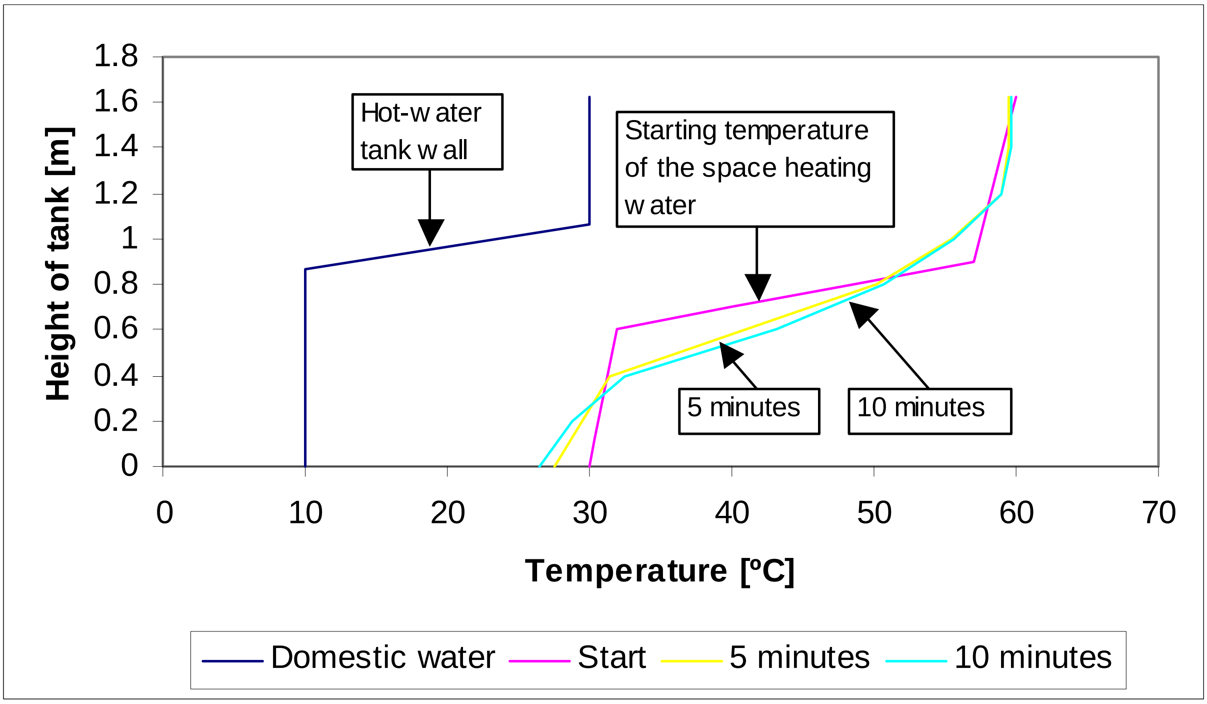

Figure 19: Calculated temperatures in the space heating storage tank at the start, after 5 minutes, and after 10 minutes at operation condition 1b.

Figure 20 shows the calculated temperatures for inlet and outlet of boiler loop and space-heating loop, respectively, plus the flow in boiler loop and space-heating loop, respectively. Both temperatures and flows are as a function of time. It appears that the inlet temperature from boiler loop to space heating storage tank and flow in boiler loop are constant at 65ºC and 10 l/min, respectively, and that the inlet temperature from the space-heating loop to space heating storage tank and flow in the space-heating loop are constant, too, with values of 20.5ºC and 0.7 l/min, respectively. The outlet temperature from space heating storage tank to boiler loop is rising from 32ºC to 42ºC, and this is a small drop compared with operation condition 1a, which is due to the fact that the space-heating loop is now in operation. The outlet temperature from space heating storage tank to space-heating loop is rising from 39º to 47ºC. During the 10 minutes of operation, the induced power from the boiler loop to the space heating storage tank falls from 22 kW to 16 kW, whereas the power delivered to the space-heating loop is rising from 0.9 kW to 1.3 kW. This means that the space-heating loop is not very important at this operation condition, as the power carried away is more than a factor of 10 smaller than the induced power from the boiler loop. That is the explanation of why the results in operation condition 1a and operation condition 1b are not very different.

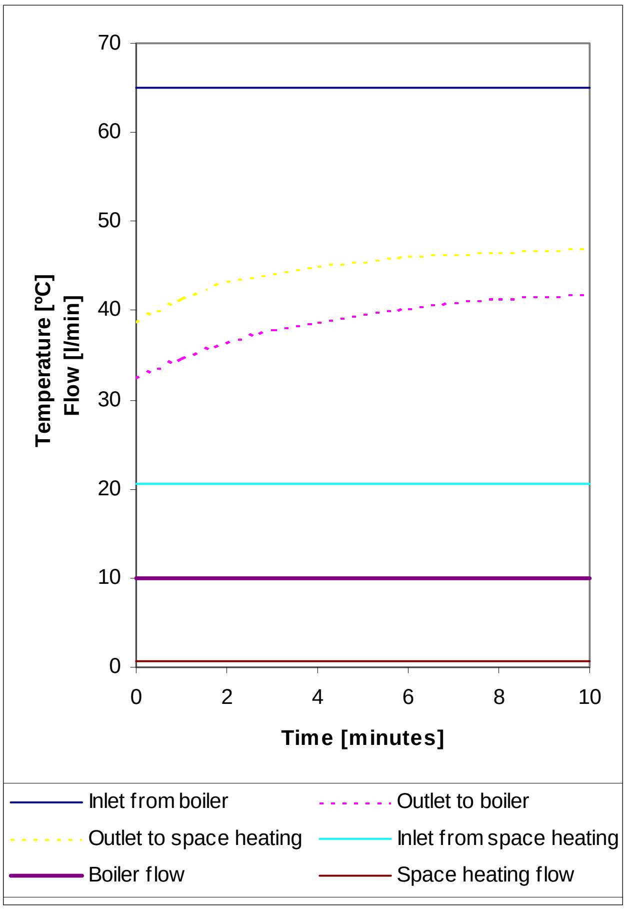

Figure 20: Inlet and outlet temperatures from boiler loop and space-heating loop, respectively, and flow in boiler loop and space-heating loop, respectively, as a function of the time for operation condition 1b. After 10 minutes in operation, the induced power from the boiler loop is 16 kW, while the power carried away to the space-heating loop is 1.3 kW.

3.2.1 Temperature and fluid motion around inlet and outlet

At operation condition 1b there is no difference in the temperature around inlet from boiler loop and fluid motion around inlet and outlet of the boiler loop compared with operation condition 1a, so these conditions are not shown. Instead is referred to Figure 9-Figure 16.

Figure 21 and Figure 22 show the temperature of the space heating water at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop (0.43 m from the bottom of the tank). It appears from Figure 21, that the temperature of the space heating water is only affected close to the inlet of the cold water coming back from the space-heating loop. It appears from Figure 22 that as the flow in the space-heating loop is not very large, the cold inlet water flows quickly from the space-heating loop downwards into the space heating storage tank because of the temperature differences. The inlet temperature of the water from the space-heating loop is 20.5ºC, whereas the temperature of the water in the space heating storage tank on a level with the inlet is 34ºC.

Figure 23 and Figure 24 show the flows at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The size of the vectors in Figure 23 and Figure 24 does not show anything about the velocity, but only something about the direction. It appears both from Figure 23 and Figure 24 that the incoming water is pouring quickly downwards in the tank, as indicated in Figure 21 and Figure 22. It can be concluded that at this operation condition the inlet to the space heating storage tank from the space-heating loop does not give cause for mixing in the space heating storage tank.

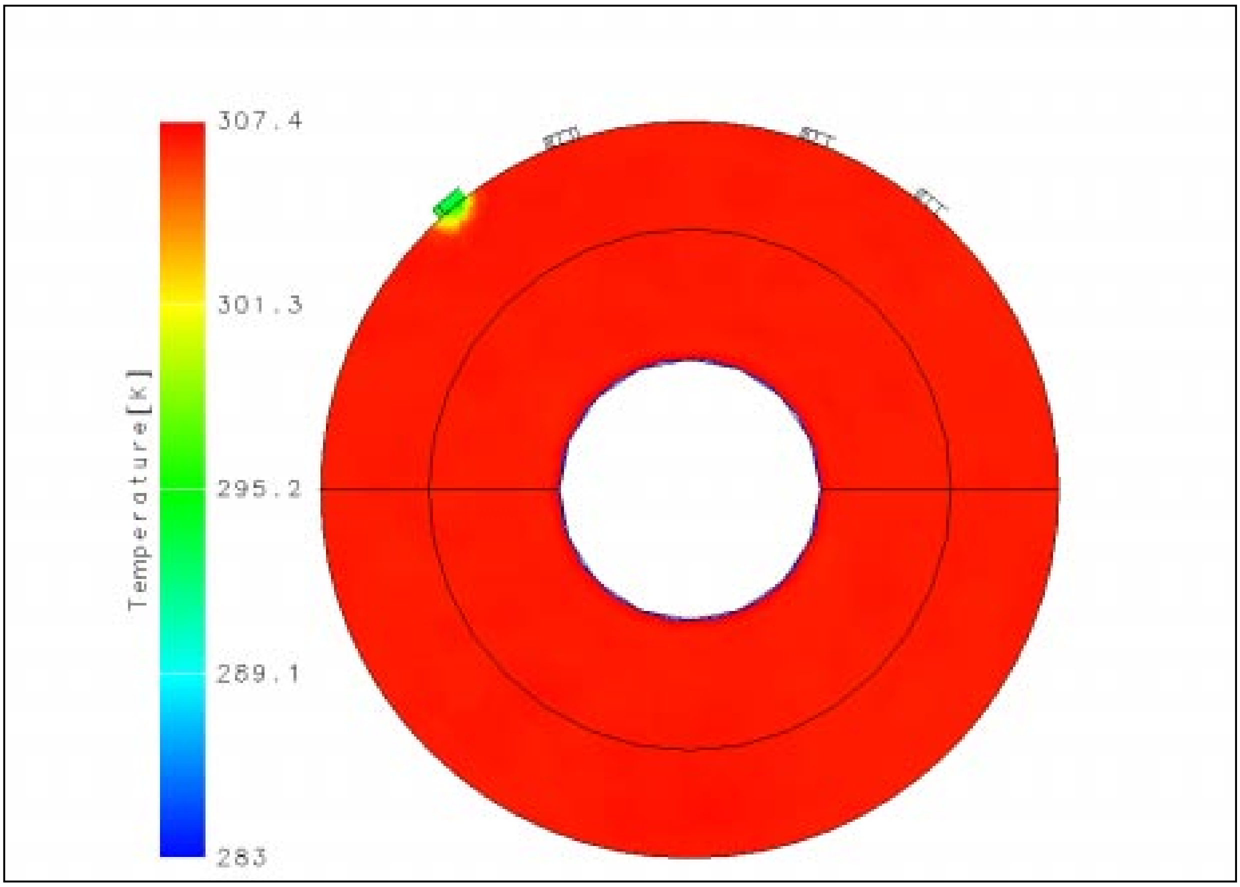

Figure 21:Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

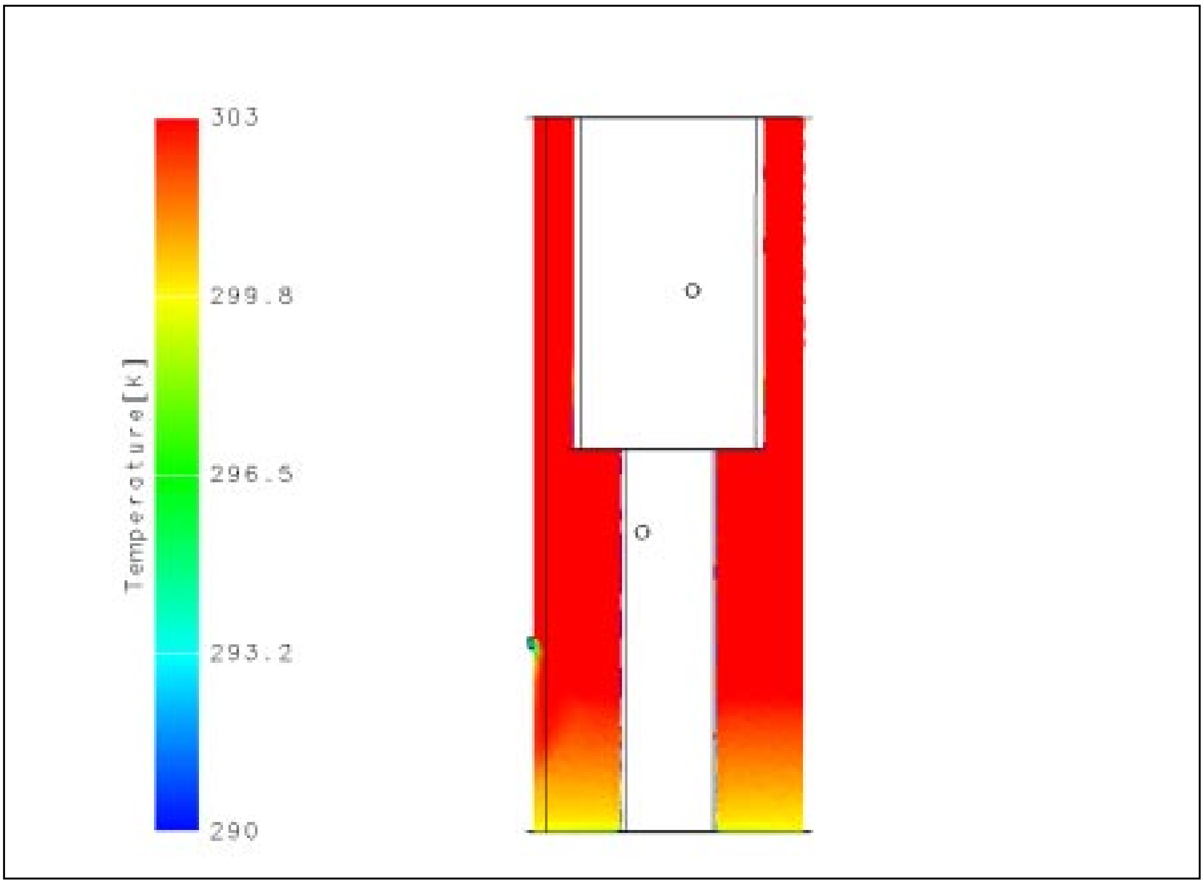

Figure 22: Calculated temperatures of the space heating water at a vertical section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

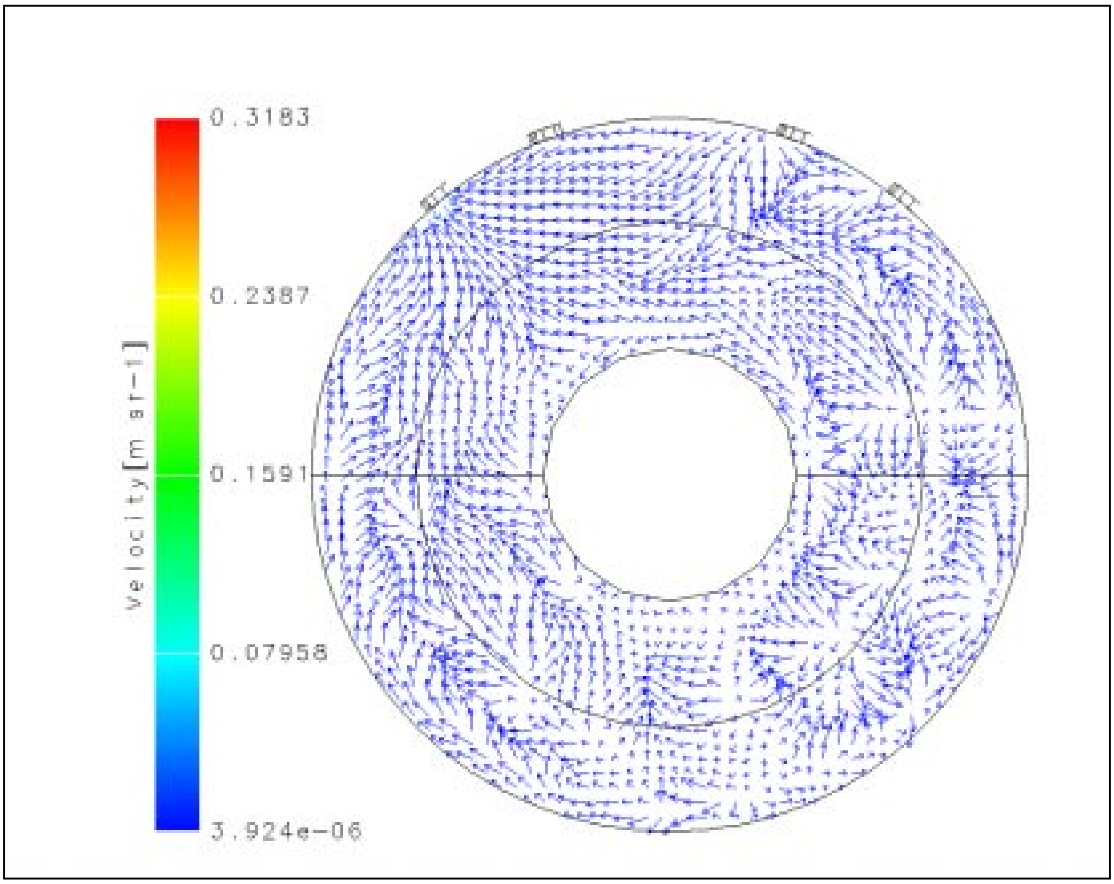

Figure 23: Vectors showing the flow in a horizontal section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

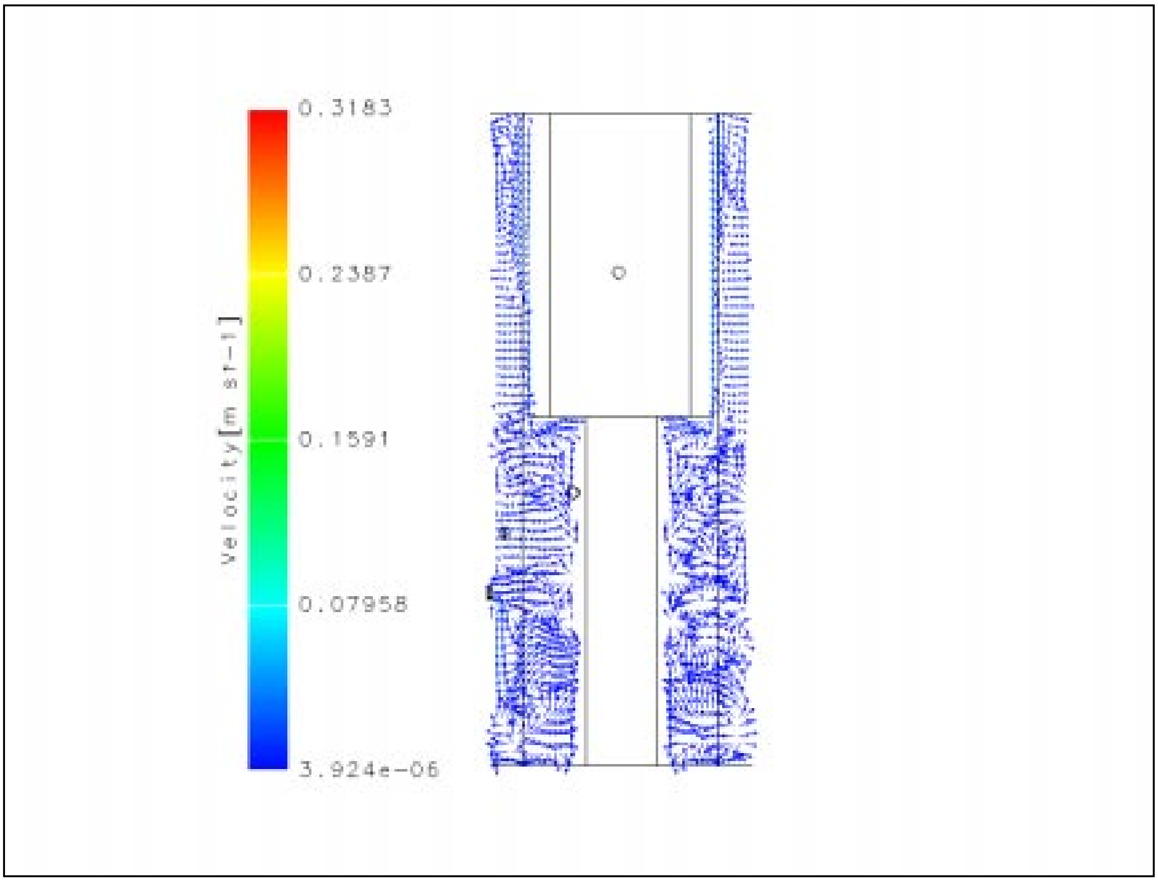

Figure 24: Vectors showing the flow in a vertical section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

Figure 25 shows the flows at a horizontal section through the outlet from the space heating storage tank to the space-heating loop (0.68 m from the bottom of the tank). The size of the vectors in Figure 25 does not show anything about the velocity, but only something about the direction. It appears that a great part of the motions in the water is directed towards the outlet to the space-heating loop. There is some disorder to the left of the inlet, however, and that is most likely because the flows are affected by the outlet to the boiler loop. The outlet to the boiler loop is 10 cm under and 20º to the left of the outlet to the space-heating loop, and at this operation condition the flow in the boiler loop is about 14 times greater than the flow in the space-heating loop.

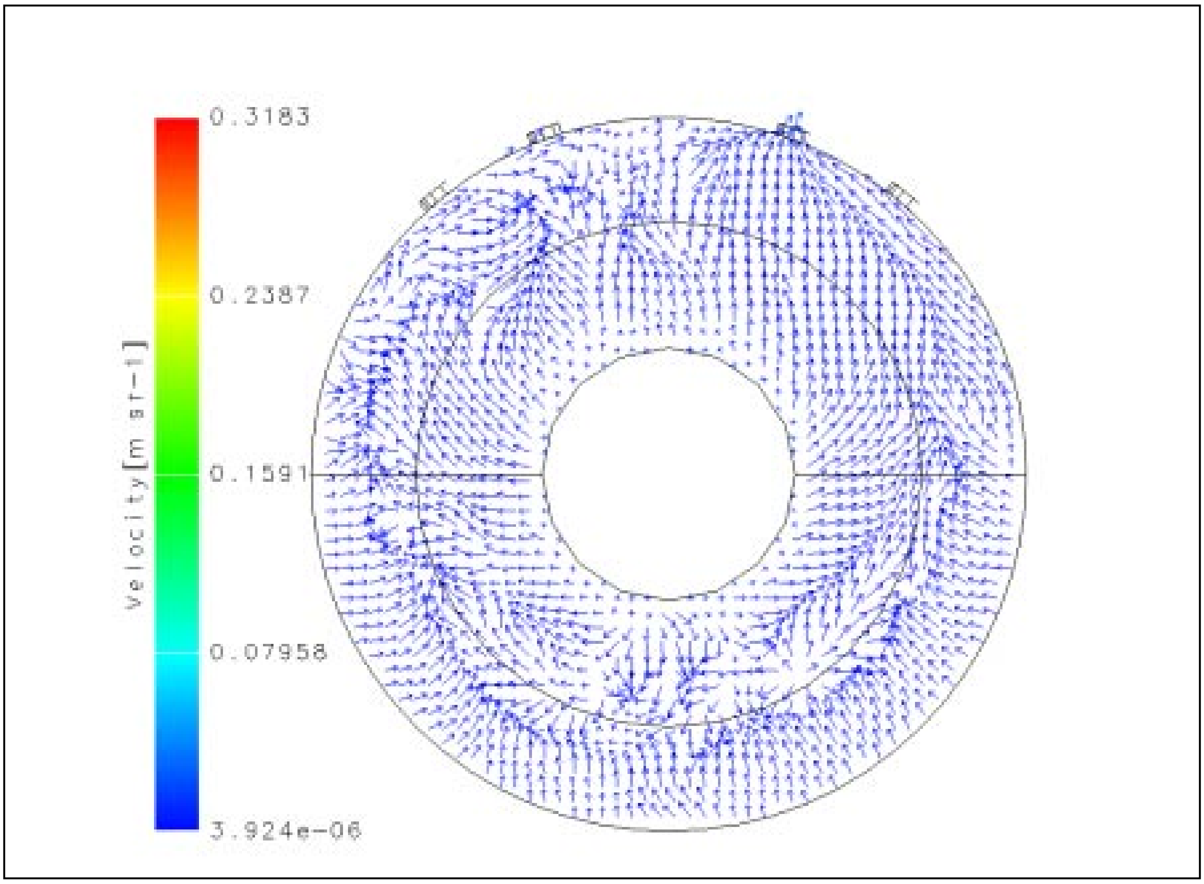

Figure 25: Vectors showing the flow in a horizontal section on a level with the outlet to the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.2.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 26shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux in Figure 26 means that the heat is transferred from the space heating water to the tank wall against the domestic water. It appears that the heat flux is largest on the middle part of the tank wall, which means just above the outlet to the boiler loop. There are two reasons for this, one is that on this level the greatest temperature difference is found between the space heating water and the tank wall against the domestic water. The other reason is that there is a good downward flow close to the tank wall against the domestic water as the water flows down towards the outlet to the boiler loop. At this operation condition the total induced power for the heat exchanger of the domestic water is 7.1 kW/m² corresponding to 13 kW.

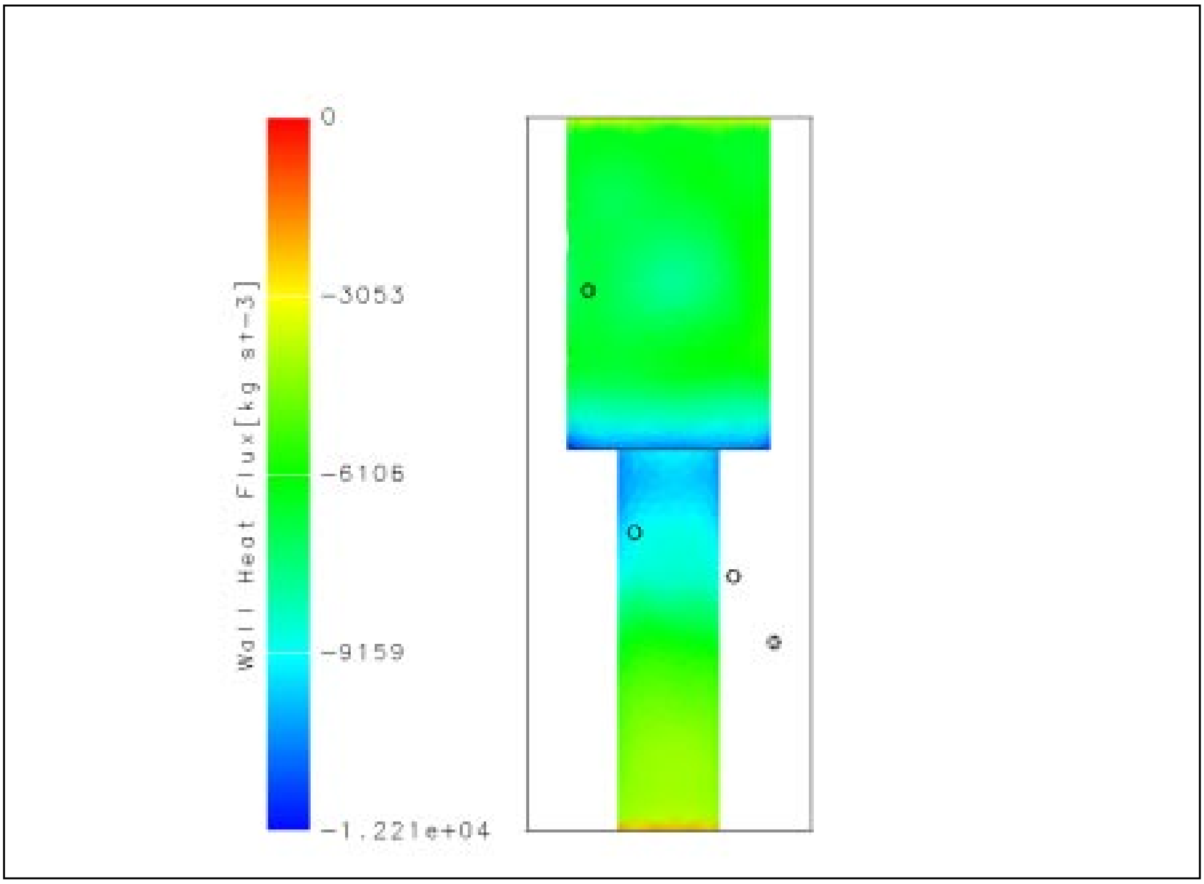

Figure 26: The calculated heat flux between the space heating water and the outside of the hot-water tank at operation condition 1b. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 27 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 210 W/m²·K and 270 W/m²·K. At this operation condition the average and total convective heat transfer coefficient, respectively, are calculated to be 243 W/m²·K and 447 W/K respectively.

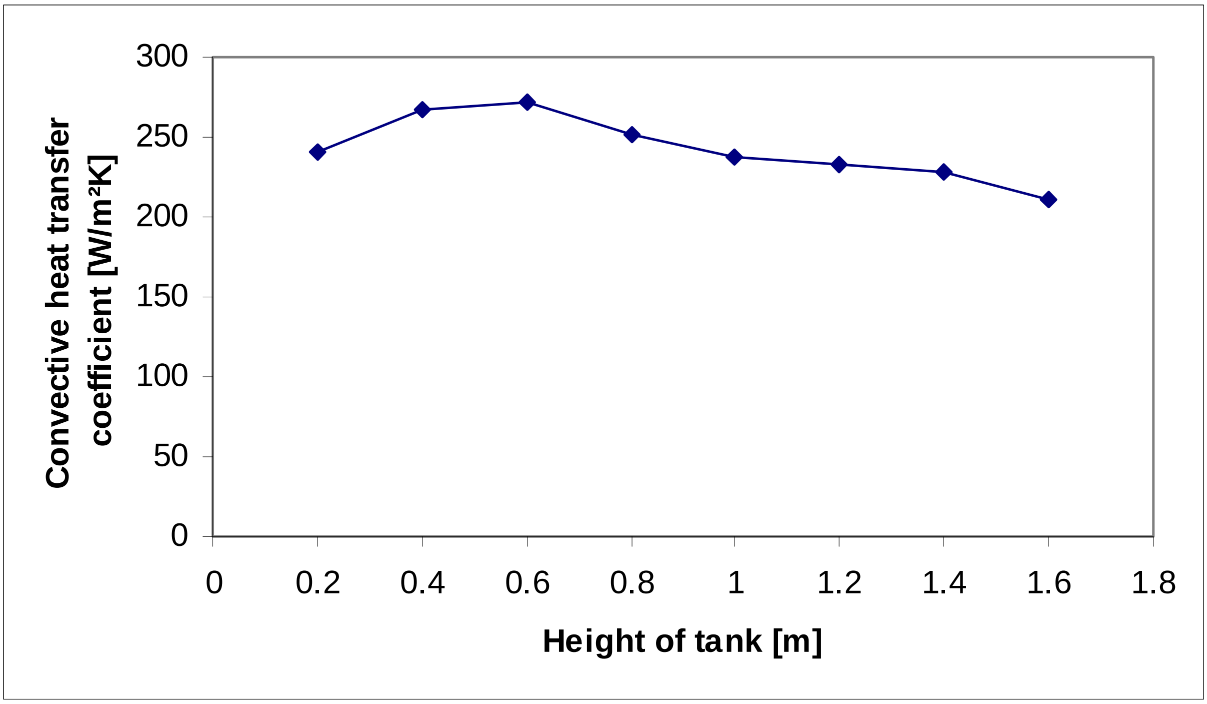

Figure 27: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 1b as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.3 Operation condition 1c

At operation condition 1c the starting temperatures indicated in Figure 5 are used. The boiler is in operation with a flow of 10 l/min and an inlet temperature of 65ºC. The space-heating loop is in operation with a flow of 1.4 l/min and an outlet temperature to the space heating storage tank of 20.5ºC.

Figure 28 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears from Figure 28 that most of the energy supply from the boiler loop is used for heating up the middle part of the space heating water. At the same time the largest change is from start to the 5th minute, whereas there is no particular change from the 5th minute to the 10th minute. Further it appears that the temperature at the top of the space heating storage tank does not exceed 60ºC although the inlet temperature from the boiler loop is 65ºC. At the same time it appears that the space-heating loop, which is in operation unlike operation condition 1a, does not influence the thermal stratification very much. The change of the flow from 0.7 l/min at operation condition 1b to 1.4 l/min has not changed the temperature profile in the space heating storage tank essentially.

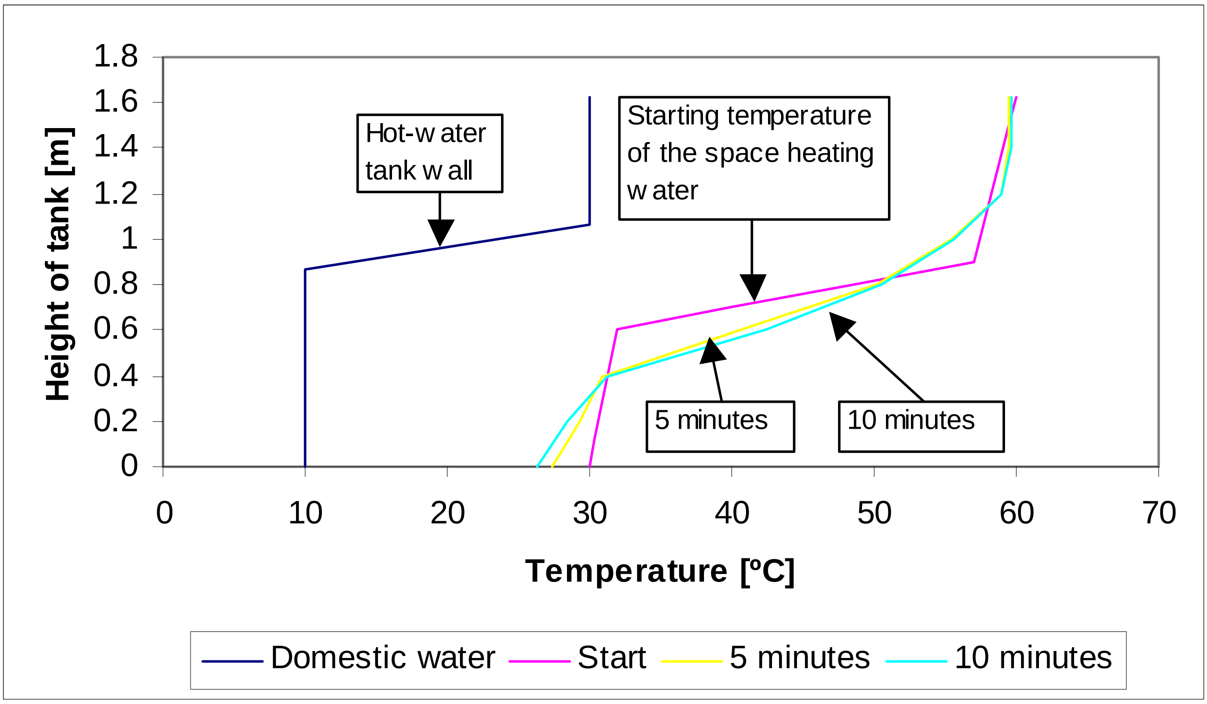

Figure 28: Calculated temperatures in the space heating storage tank at the start, after 5 minutes, and after 10 minutes at operation condition 1c.

Figure 29 shows the calculated temperatures for inlet and outlet of boiler loop and space-heating loop, respectively, and the flow in boiler loop and space-heating loop, respectively. Both temperatures and flows are as a function of the time. It appears that the inlet temperature from boiler loop to space heating storage tank and flow in boiler loop are constant at 65ºC and 10 l/min, respectively, and that the inlet temperature from the space-heating loop to space heating storage tank and flow in the space-heating loop are constant, too, with values of 20.5ºC and 1.4 l/min, respectively. The outlet temperature from space heating storage tank to boiler loop rises from 32ºC to 41ºC, and this is a small drop compared with operation condition 1a, which is due to the fact that the space-heating loop is now in operation. The outlet temperature from space heating storage tank to space-heating loop rises from 39º to 47ºC. The induced power from the boiler loop to the space heating storage tank falls during the 10 minutes' operation from 22 kW to 17 kW, whereas the power delivered to the space-heating loop rises from 1.7 kW to 2.5 kW. This means that the space-heating loop is not very important at this operation condition, as the power carried away is a factor of 7 smaller than the induced power from the boiler loop. That is the explanation of why the results in operation condition 1a and operation condition 1b are not very different.

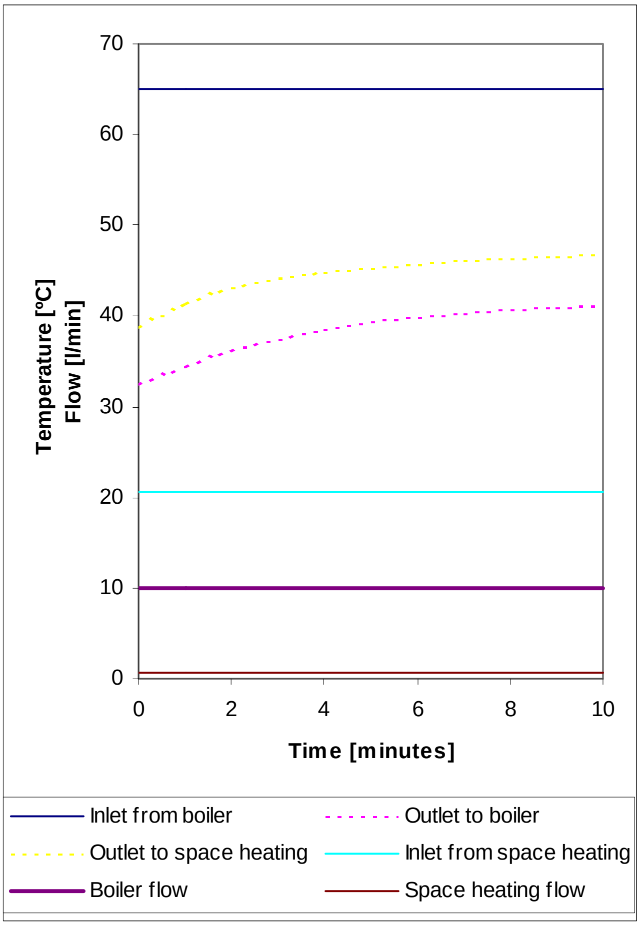

Figure 29: Inlet and outlet temperatures from boiler loop and space-heating loop, respectively, and flow in boiler loop and space-heating loop, respectively, as a function of the time for operation condition 1c. After 10 minutes' operation the induced power from the boiler loop is 17 kW, whereas the power carried away to the space-heating loop is 2.5 kW.

3.3.1 Temperature and fluid motion around inlet and outlet

At operation condition 1c there is no difference in the temperature around inlet from boiler loop and fluid motion around inlet and outlet of the boiler loop compared with operation condition 1a and operation condition 1b, so these conditions are not shown. Instead is referred to Figure 9-Figure 16.

Figure 30and Figure 31 show the temperature of the space heating water at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The same tendency as at operation condition 1b has its effect as the temperature in the space heating water is only affected close to the inlet before the in-pouring water goes downwards in the space heating storage tank because of the temperature difference. If Figure 30 and Figure 31 are compared with Figure 21 and Figure 22 it appears that the larger flow in the space-heating loop in operation condition 1c has the result that the inlet flow affects the temperature a little farther away from the inlet than at operation condition 1b. The weighted temperature of the space heating water at the same level as in Figure 30 is 33ºC at operation condition 1c, whereas it is 34ºC at operation condition 1b.

Figure 32 and Figure 33 show the flows at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The size of the vectors in Figure 32 and Figure 33 does not show anything about the velocity, but only something about the direction. It appears, both from Figure 32 and Figure 33, that the incoming water flows quickly downwards in the tank, and that it gets somewhat further into the space heating storage tank than at operation condition 1b before it flows downwards. It can be concluded that at this operation condition the inlet to the space heating storage tank from the space-heating loop only gives cause for minimal mixing in the space heating storage tank.

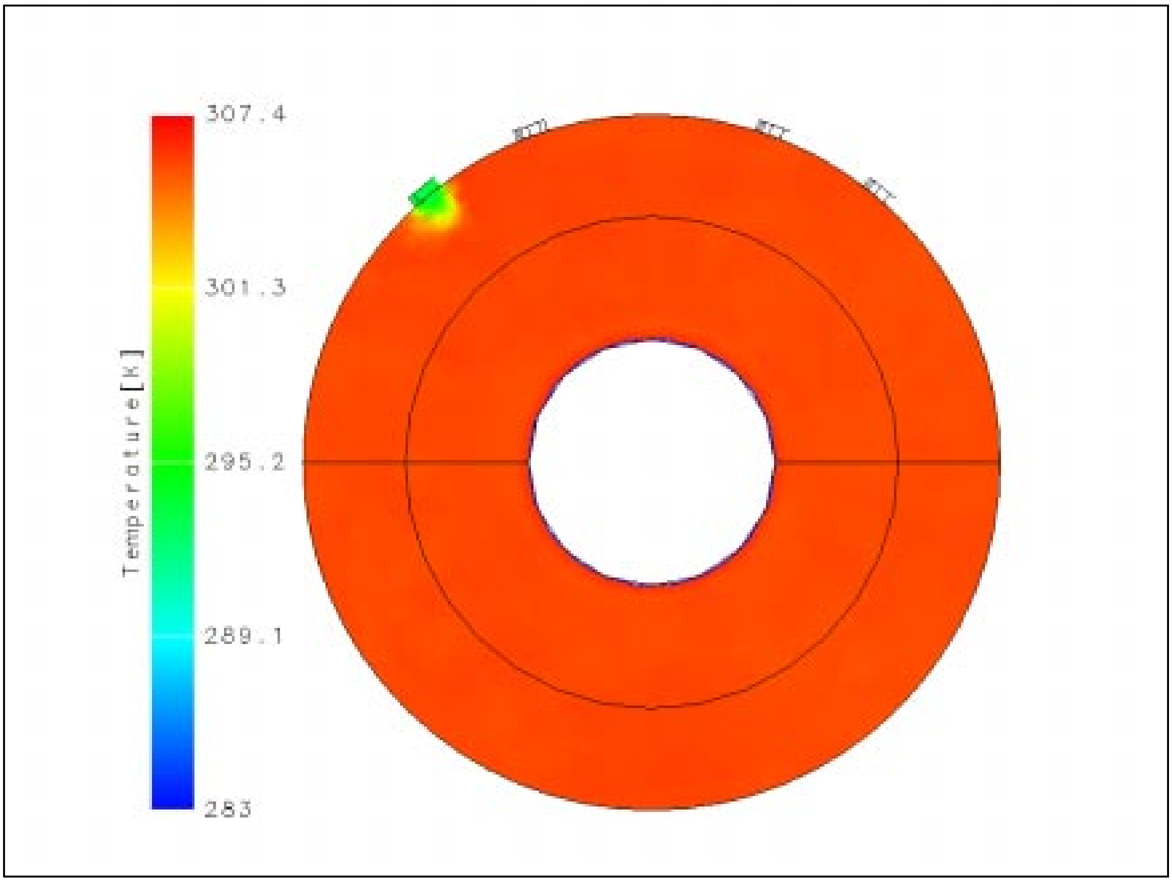

Figure 30: Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

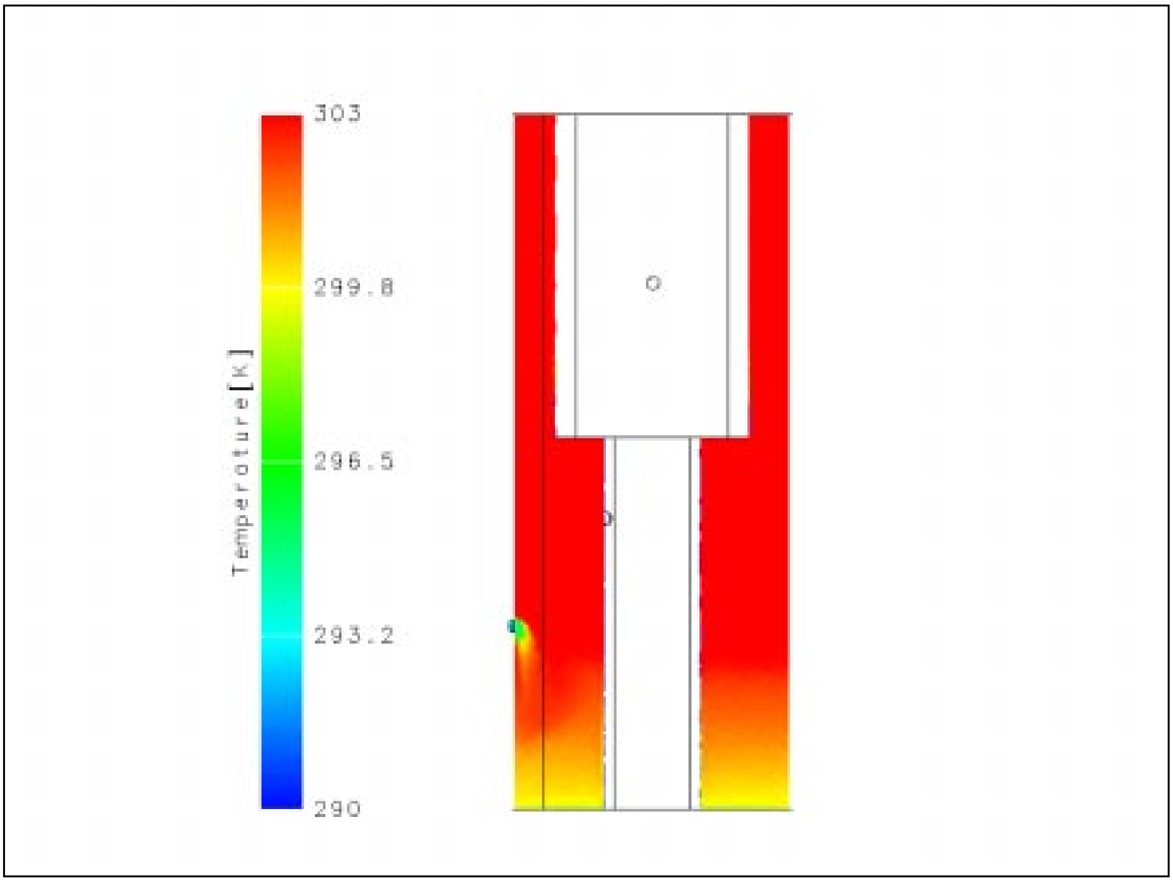

Figure 31: Calculated temperatures of the space heating water at a vertical section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

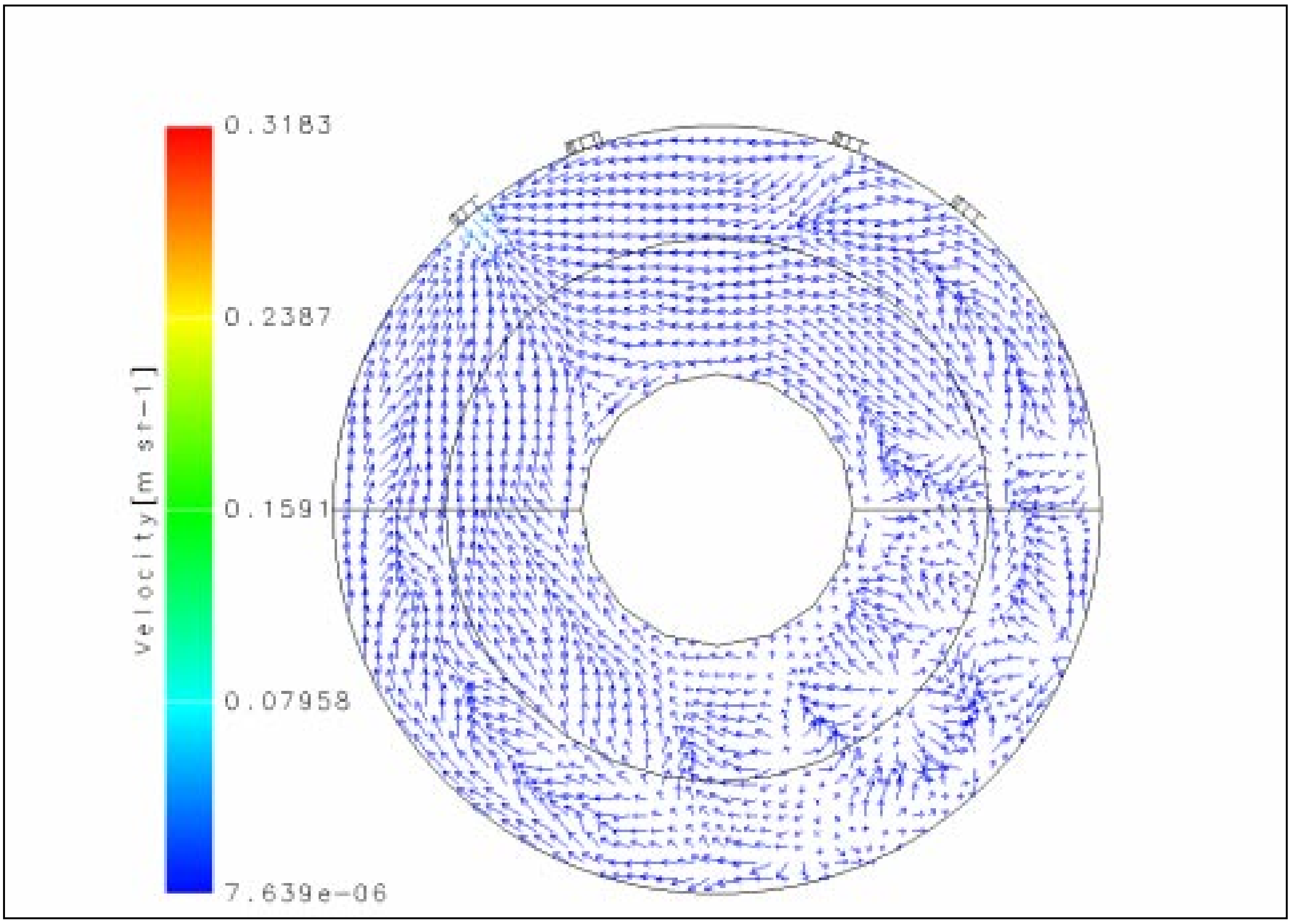

Figure 32: Vectors showing the flow in a horizontal section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

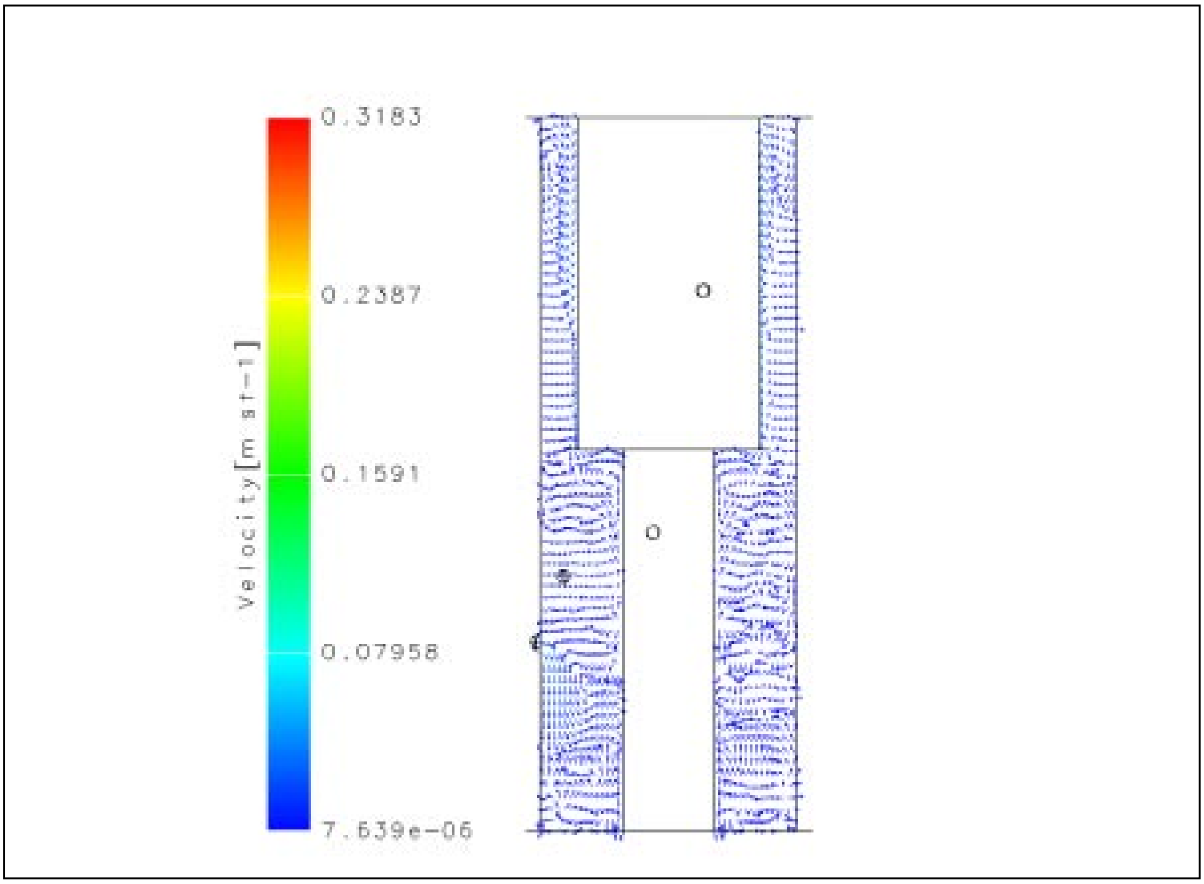

Figure 33: Vectors showing the flow in a vertical section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.3.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between the water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 34 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux on Figure 34 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that the heat flux is largest on the middle part of the tank wall, i.e. just above the outlet to the boiler loop. There are two reasons for this, one is that the largest temperature difference between space heating water and tank wall against domestic water occurs at this level. The other reason is that there is a good downward flow close to the tank wall against the domestic water as the water flows down towards the outlet to the boiler loop. At this operation condition the total induced power for the heat exchanger of the domestic water is 7.1 kW/m² corresponding to 13 kW.

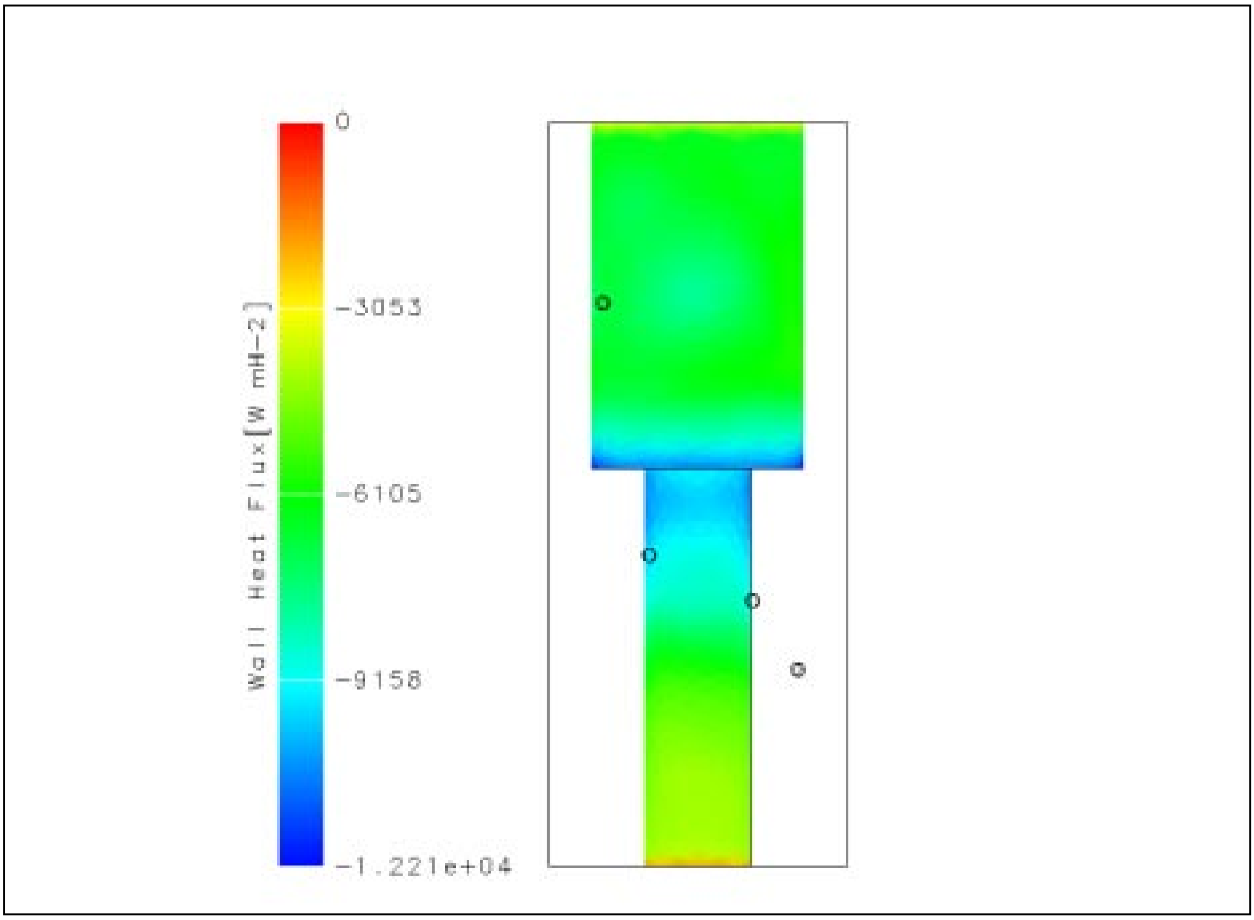

Figure 34: The calculated heat flux between space heating water and the outside of hot-water tank at operation condition 1c. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 35 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 219 W/m²·K and 270 W/m²·K. At this operation condition the average and total convective heat transfer coefficients, respectively, are calculated to be 244 W/m²·K and 449 W/K, respectively.

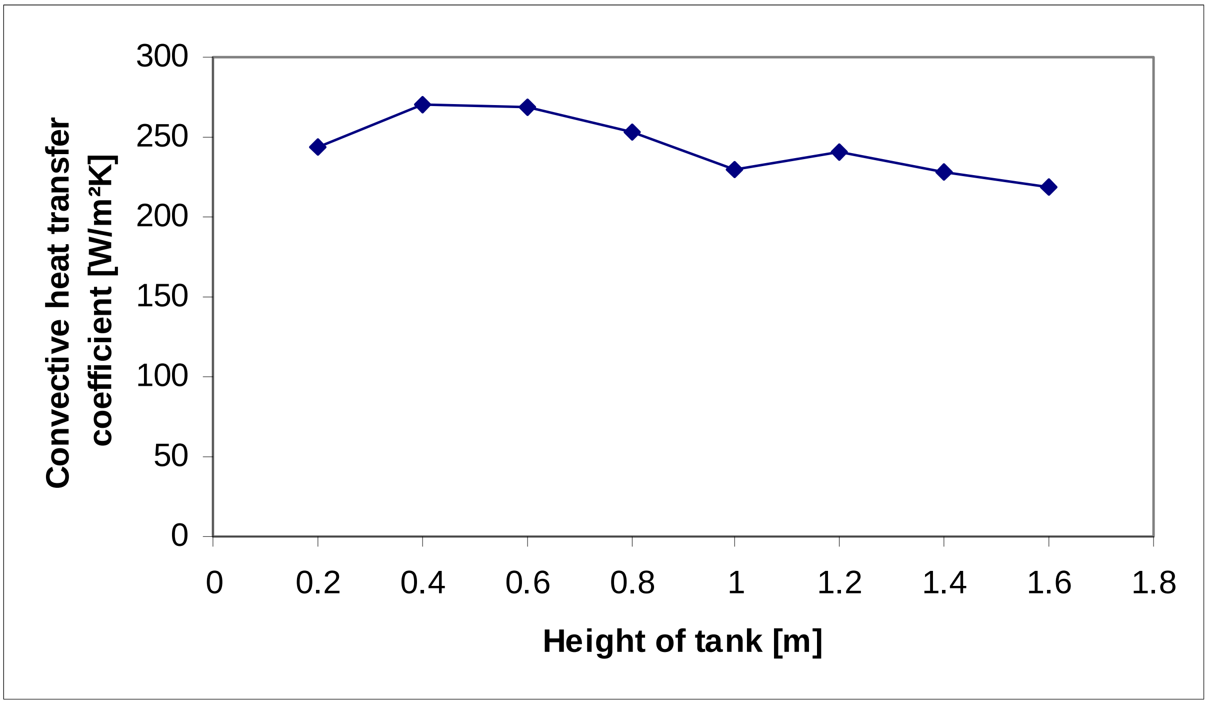

Figure 35: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 1c as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.4 Operation condition 2a

At operation condition 2a the starting temperatures indicated in Figure 6 are used. The boiler is in operation with a flow of 10 l/min and an inlet temperature of 65ºC. The space-heating loop is not in operation.

Figure 36 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears from Figure 36 that most of the energy supply from the boiler loop is used for heating up the upper part of the space heating water. The temperature at the top does not exceed 60ºC during the 10 minutes, however. The changes from the start to the 5th minute are approximately as large as the changes from the 5th minute to the 10th minute. These observations are somewhat different from the observations at operation condition 1a. This is primarily due to the fact that at operation condition 2a the difference is not very great between the starting temperatures for tank wall against domestic water and for the space heating water, respectively.

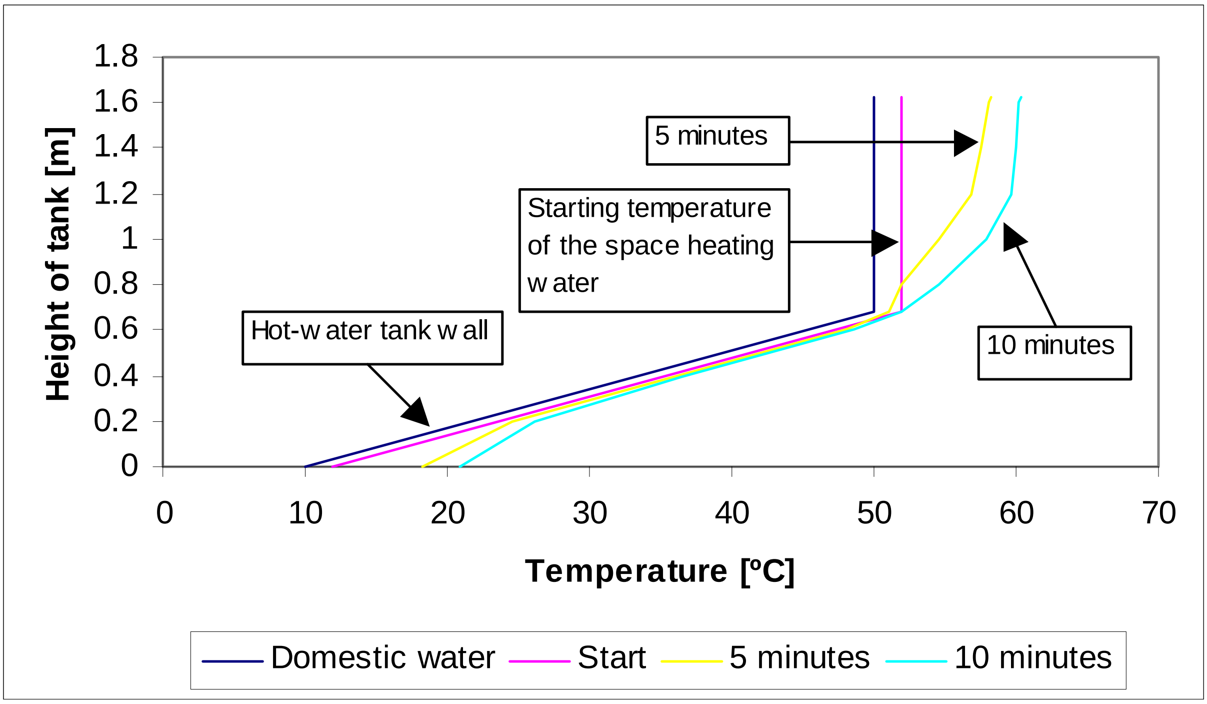

Figure 36: Calculated temperatures in the space heating storage tank at the start, after 5 minutes, and after 10 minutes at operation condition 2a.

Figure 37 shows the calculated temperatures for inlet and outlet of the boiler loop and the flow in the boiler loop as a function of the time. It appears that the inlet temperature from boiler loop to space heating storage tank and flow in the boiler loop are constant at 65ºC and 10 l/min, respectively. The outlet temperature from space heating storage tank to boiler loop is also almost constant, it rises from 46ºC to 47ºC. The induced power from the boiler loop at operation condition 2a goes to heating up the space heating water at the top of the space heating storage tank, and that is the reason why the outlet temperature to the boiler loop does not rise as much as at operation condition 1a. The induced power from the boiler loop to the space heating storage tank falls during the 10 minutes' operation from 13 kW to 12 kW.

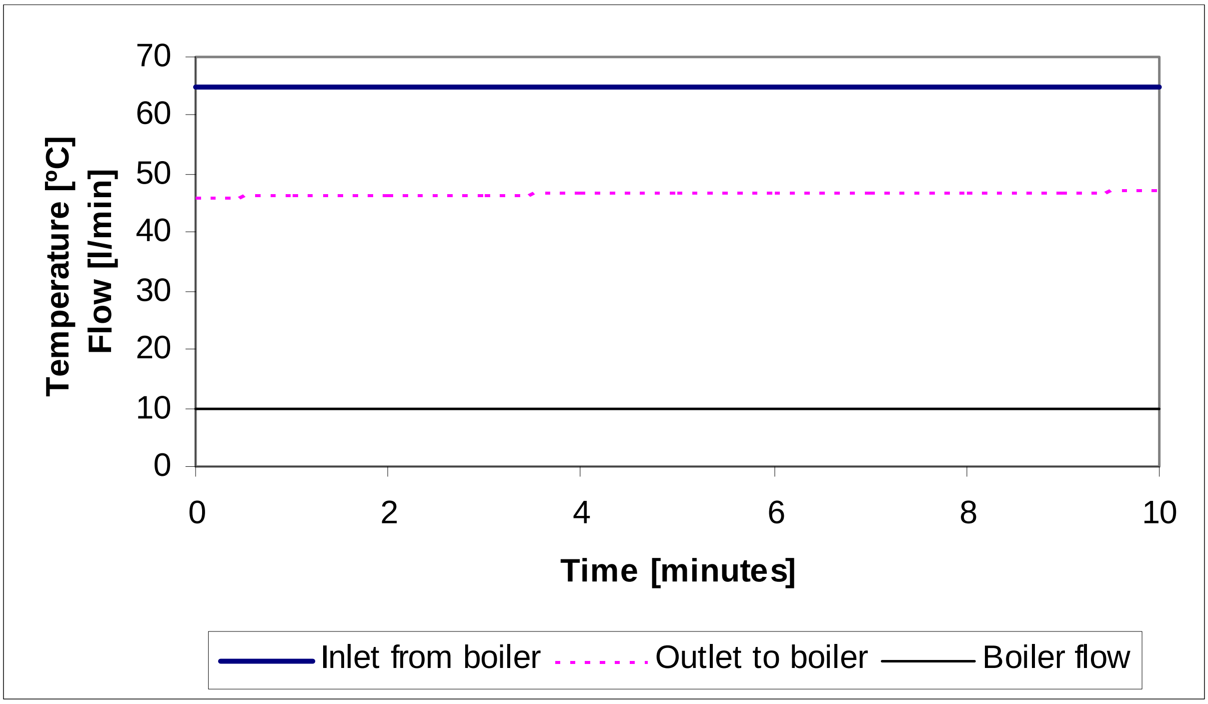

Figure 37: Inlet and outlet temperatures from the boiler loop and flow in the boiler loop as a function of the time for operation condition 2a. The induced power from the boiler loop is 12 kW after 10 minutes in operation.

3.4.1 Temperature and fluid motion around inlet and outlet

Figure 38 shows the temperature of the space heating water in a horizontal section on a level with the inlet from the boiler loop. Figure 39 shows the flows in a horizontal section on a level with the inlet from the boiler loop, and there is no connection between the sizes of the vectors in Figure 39 and the size of the flow, they only indicate the direction of the flow. In operation condition 1a the temperature of the inlet water from the boiler loop was approximately 5 K higher than the temperature of the water in the space heating storage tank on a level with the inlet, whereas the temperature of the inlet water from the boiler loop at operation condition 2a is approximately. 15 K higher than the temperature of the water in the space heating storage tank on a level with the inlet. If Figure 38 and Figure 39 are compared with Figure 9 and Figure 11 it appears that this change from operation condition 1a to 2a does not change the flow pattern on the level with the inlet. Figure 40 shows the flow in a vertical section on a level with the inlet from the boiler loop. If Figure 40 is compared with Figure 12 it appears that there is a slightly difference in the flow in the top of the space heating tank. At operation condition 2a the recirculation in the same side as the inlet from the boiler is moved a little bit up towards the top of the tank while the flow around the hot-water tank in the opposite side of the inlet is forced a little bit down.

Figure 41 shows the flows in a horizontal section on a level with the outlet to the boiler loop, and the sizes of the vectors in Figure 41 have no connection with the sizes of the flows, they only indicate the direction of the flow. It appears that at this operation condition the flow pattern at this level is almost identical to the flow pattern at the same level at operation condition 1a.

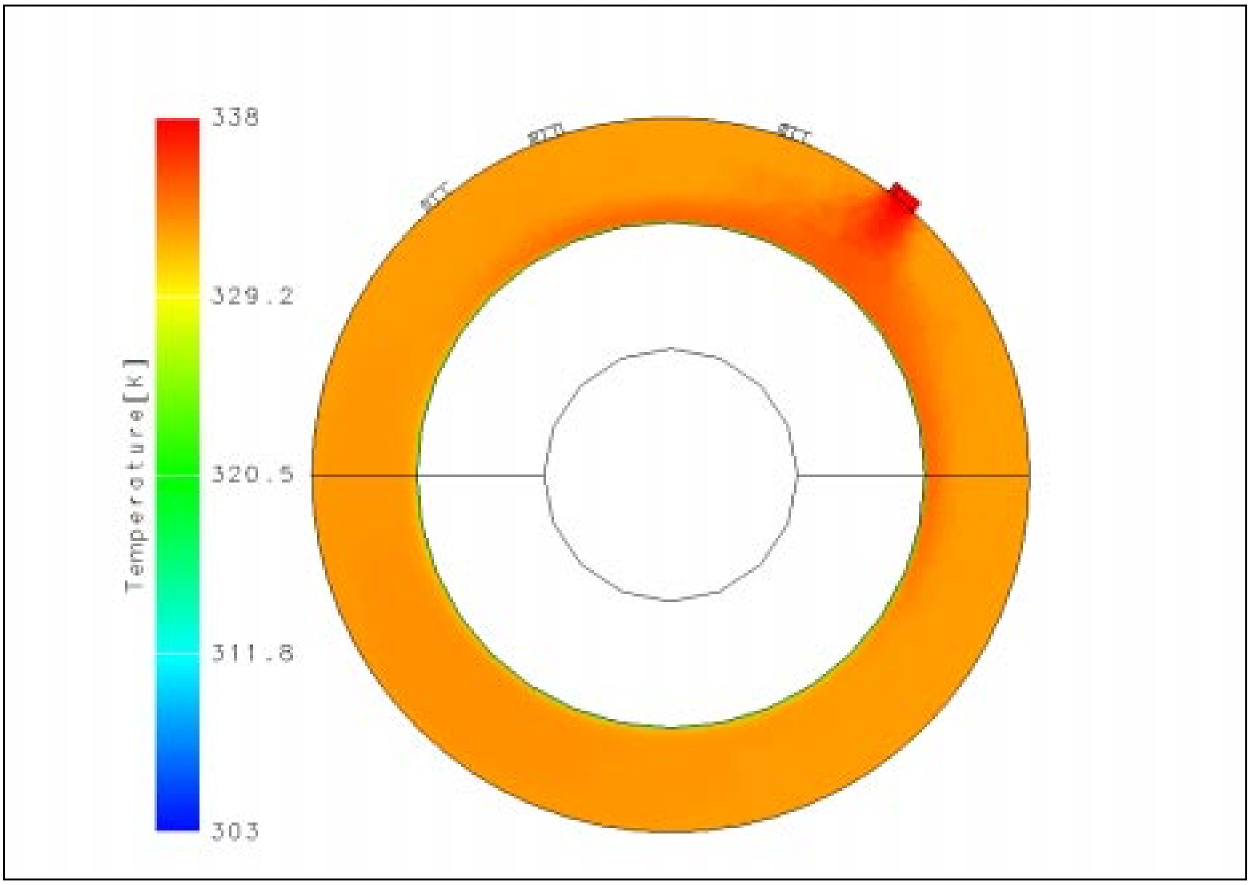

Figure 38: Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the boiler loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

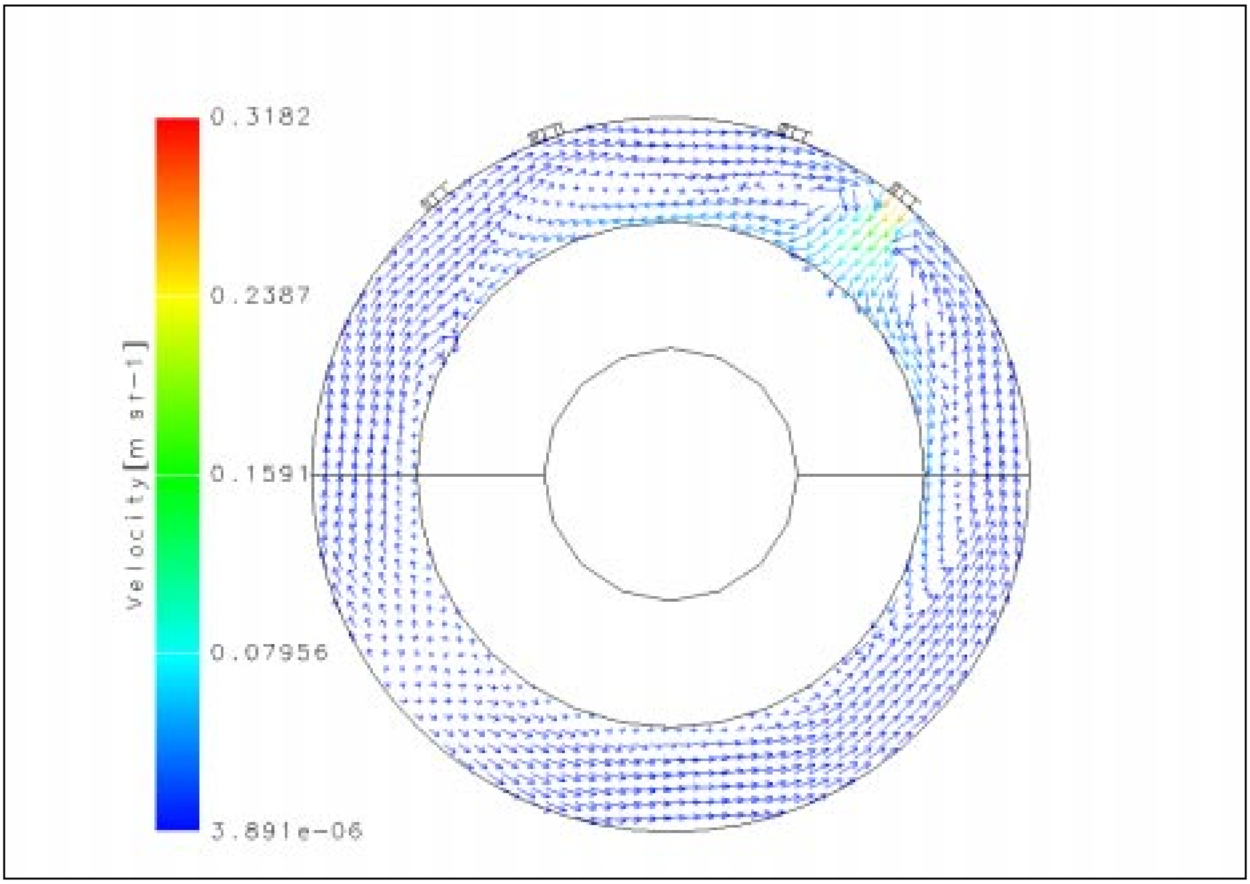

Figure 39: Vectors showing the flow in a horizontal section on a level with the inlet from the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

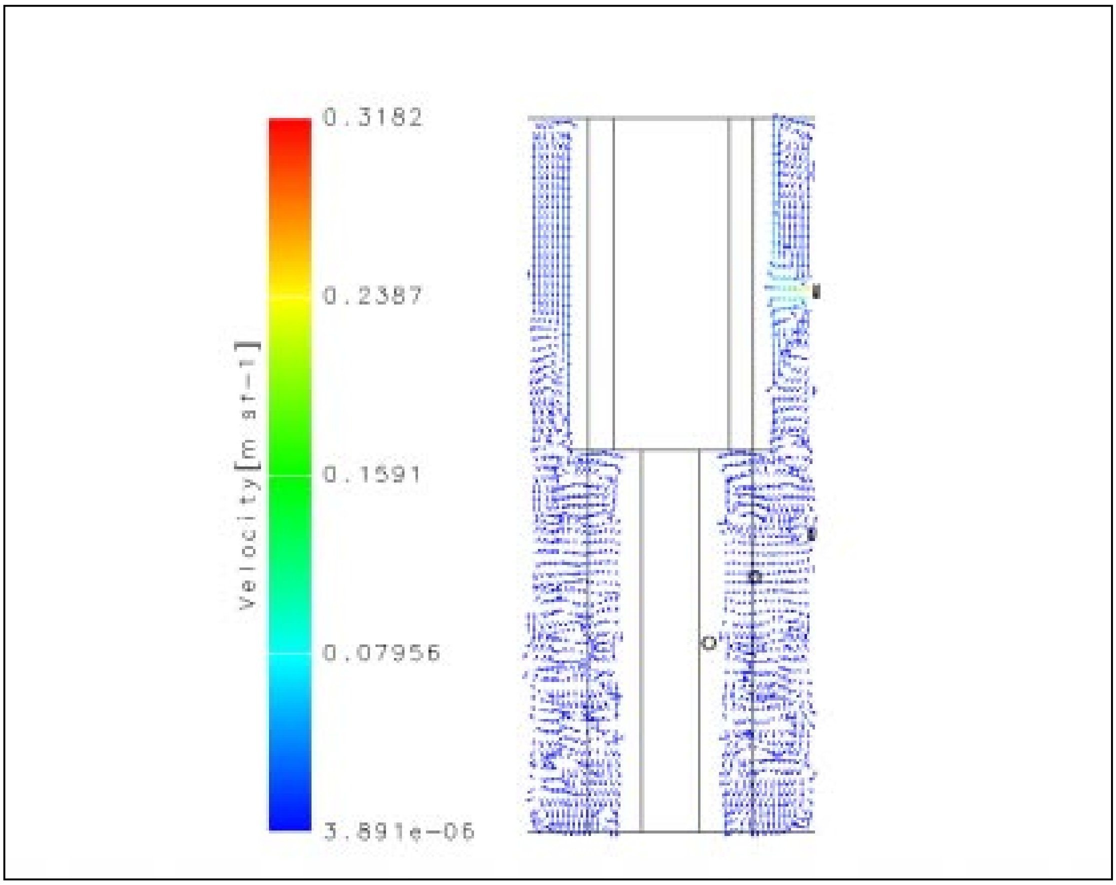

Figure 40: Vectors showing the flow in a vertical section on a level with the inlet from the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

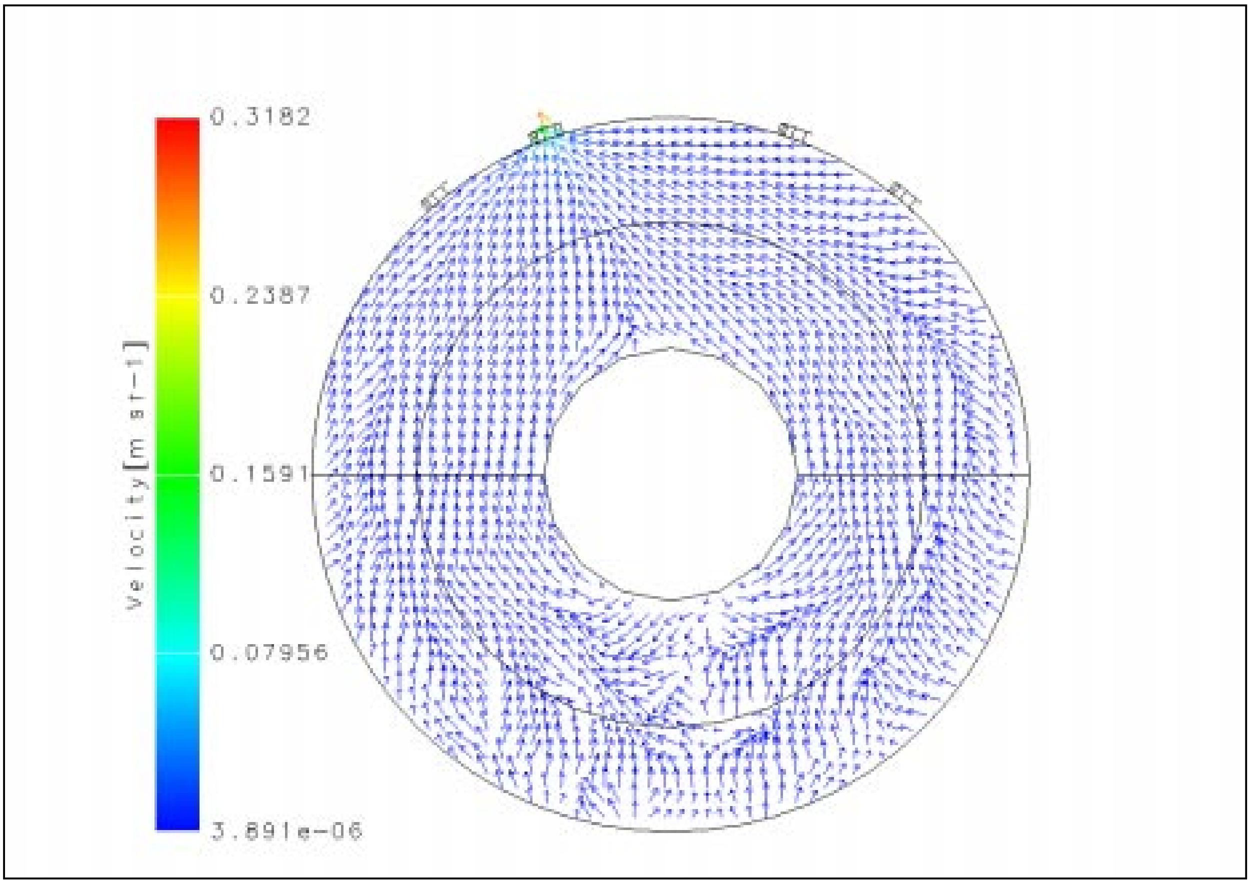

Figure 41: Vectors showing the flow in a horizontal section on a level with the outlet to the boiler loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.4.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 42 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux on Figure 42 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that the heat flux is greatest on the upper part of the tank wall on a level with the inlet from the boiler loop. This is not surprising as the inlet flow at this operation condition is dominating for the heat transfer between space heating water and outside of hot-water tank in contrast to operation condition 1a, where the large temperature difference between space heating water and outside of hot-water tank was dominating. The total transferred power from the space heating storage tank to the hot-water tank is 1.7 kW/m² corresponding to 3.1 kW at this operation condition.

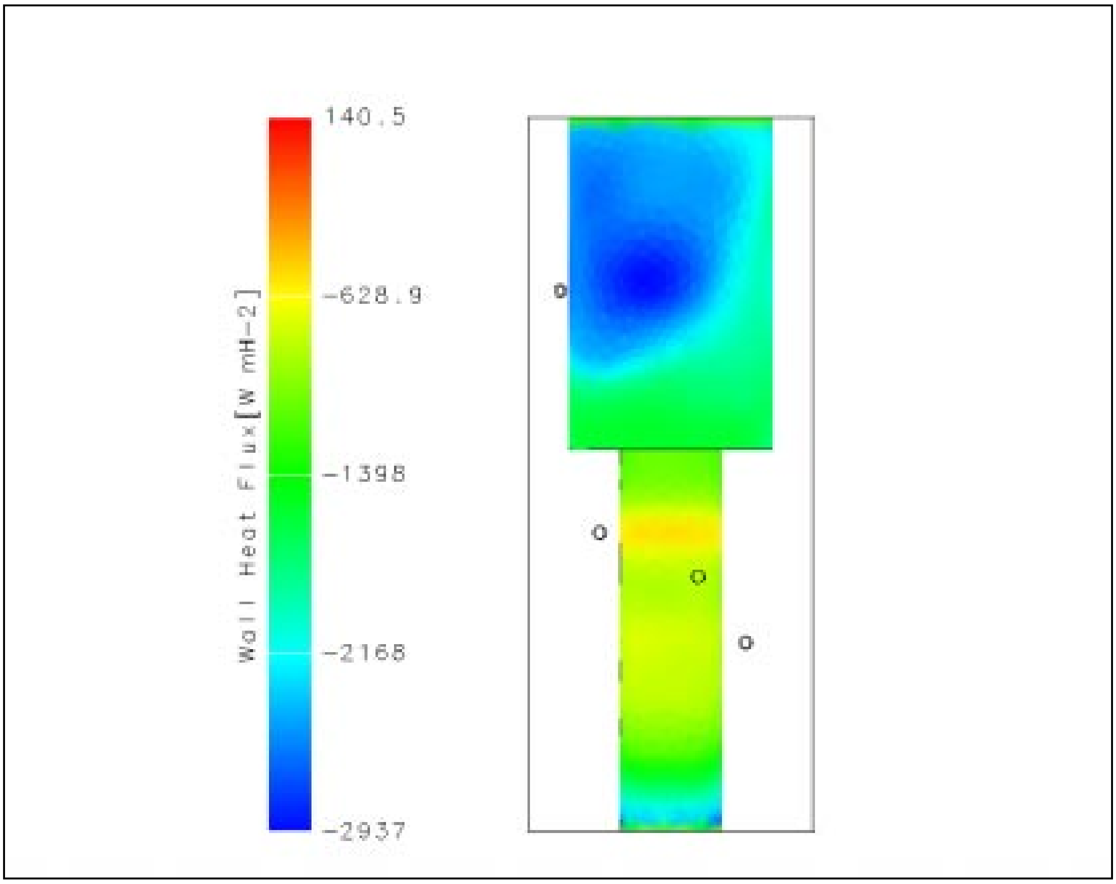

Figure 42: The calculated heat flux between space heating water and outside of hot-water tank at operation condition 2a. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 43 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 200 $W/m^2 \cdot K$ and 270 $W/m^2 \cdot K$. At this operation condition, the average and the total convective heat transfer coefficient, respectively, are calculated to be 236 $W/m^2 \cdot K$ and 434 W/K, respectively.

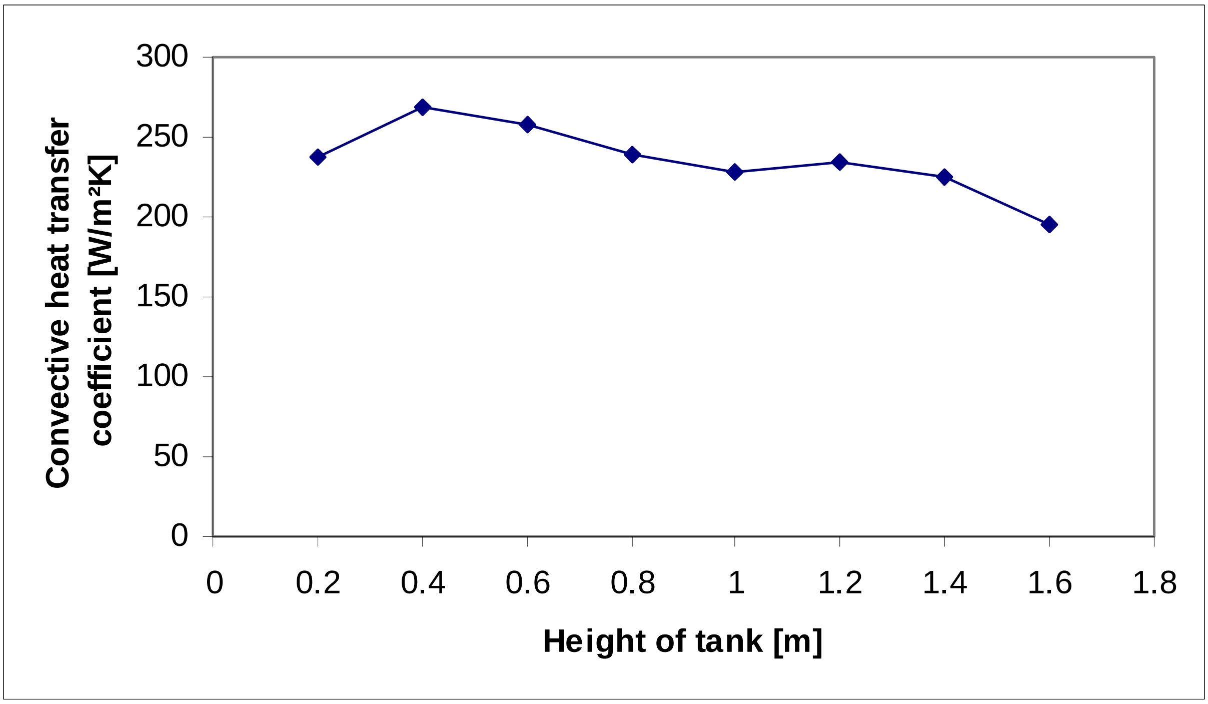

Figure 43: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 2a as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.5 Operation condition 2b

At operation condition 2b the starting temperatures given in Figure 6 are used. The boiler is in operation with a flow of 10 l/min and an inlet temperature of 65ºC. The space-heating loop is in operation with a flow of 1.4 l/min and an outlet temperature to the space heating storage tank of 20.5ºC.

Figure 44 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears from Figure 44 that the greater part of the energy supply from the boiler loop goes to heating up the upper part of the space heating water. The temperature at the top does not exceed 60ºC in the 10 minutes, however. At the same time it appears that the space-heating loop, which is in operation unlike operation condition 1a, is insignificant for the temperature at the level around the inlet from the space-heating loop. The difference between the temperature of the water in the space heating storage tank on a level with the inlet from the space-heating loop (0.43 m from the bottom of the tank) at operation condition 2a and 2b, respectively, is approximately 3 K.

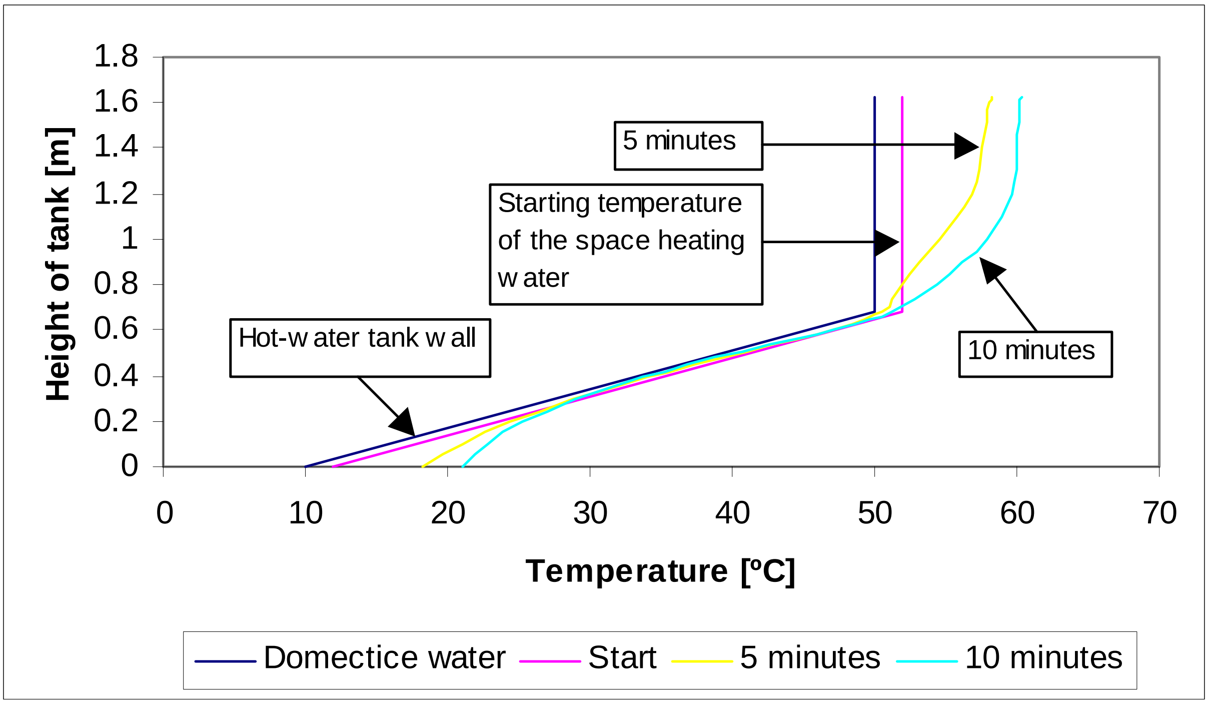

Figure 44: Calculated temperatures in the space heating storage tank at start, after 5 minutes, and after 10 minutes at operation condition 2b.

Figure 45 shows the calculated temperatures for inlet and outlet of boiler loop and space-heating loop, respectively, and the flow in boiler loop and space-heating loop, respectively. Both temperatures and flows are as a function of the time. It appears that the inlet temperature from boiler loop to space heating storage tank and the flow in boiler loop are constant at 65ºC and 10 l/min, respectively, and that the inlet temperature from the space-heating loop to space heating storage tank and flow in the space-heating loop are constant, too, with values of 20.5ºC and 1.4 l/min, respectively. The outlet temperature from space heating storage tank to boiler loop is fairly constant about 46ºC. The outlet temperature from space heating storage tank to space-heating loop is fairly constant about 51ºC. After 10 minutes in operation the induced power from the boiler loop to the space heating storage tank is 13 kW, whereas the power carried away to the space-heating loop is 3 kW.

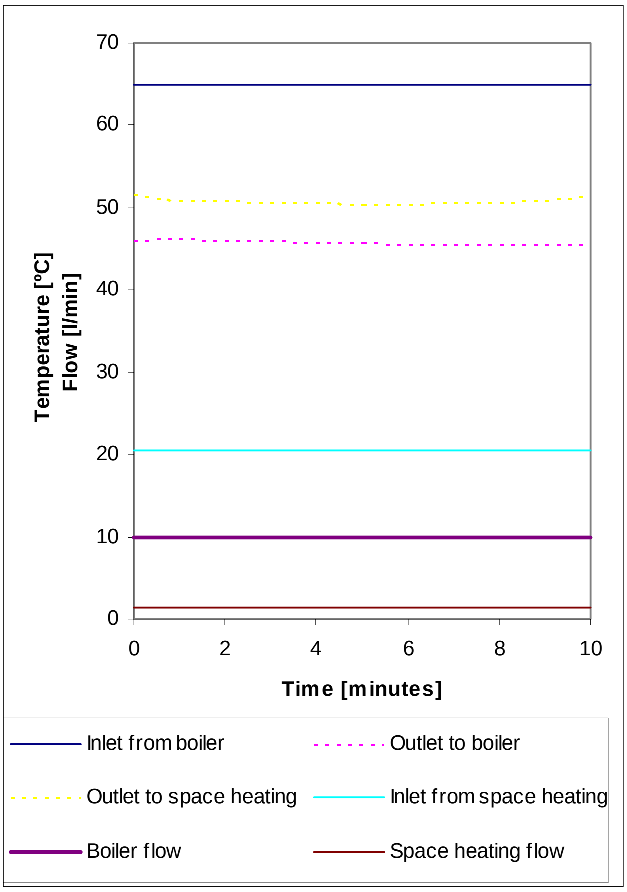

Figure 45: Inlet and outlet temperatures from boiler loop and space-heating loop, respectively, and flow in boiler loop and space-heating loop, respectively, as a function of the time for operation condition 2b. The induced power from the boiler loop is 13 kW after 10 minutes in operation, whereas the power carried away to the space-heating loop is 3 kW.

3.5.1 Temperature and fluid motion around inlet and outlet

At operation condition 2b there is no difference in the temperature around inlet from boiler loop and fluid motion around inlet and outlet for the boiler loop compared to operation condition 2a. This is therefore not shown, but referred to in Figure 38 - Figure 41.

Figure 46 and Figure 47 show the temperature of the space heating water at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. Figure 48and Figure 49 show the flows at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The size of the vectors in Figure 48 and Figure 49 does not show anything about the velocity, but only something about the direction.

It appears from Figure 46 that the temperature of the space heating water is only affected close to the inlet of the cold water coming back from the space-heating loop. It appears from Figure 47 that as the flow in the space-heating loop is not very large, the cold inlet water flows quickly from the space-heating loop downwards into the space heating storage tank because of the temperature differences. The inlet temperature of the water from the space-heating loop is 20.5ºC, whereas the temperature of the water in the space heating storage tank on a level with the inlet is 36ºC. It also appears from Figure 48 and Figure 49 that the incoming water is pouring quickly downwards in the tank, just as it was indicated by Figure 46 and Figure 47. It can be concluded that at this operation condition the inlet to the space heating storage tank from the space-heating loop does not give cause for mixing in the space heating storage tank.

If Figure 48 and Figure 49 are compared with Figure 32 and Figure 33 (which show the same flows at operation condition 1c) it appears that the fluid motions are very much alike, especially on the horizontal level. On the vertical level there is the difference that at operation condition 1c the water (Figure 33) goes further down into the tank before it finds a place with thermal equilibrium. This is due to the fact that the temperature of the water in the space heating storage tank under the level of the inlet from the space-heating loop is higher for operation condition 1c than for operation condition 2b.

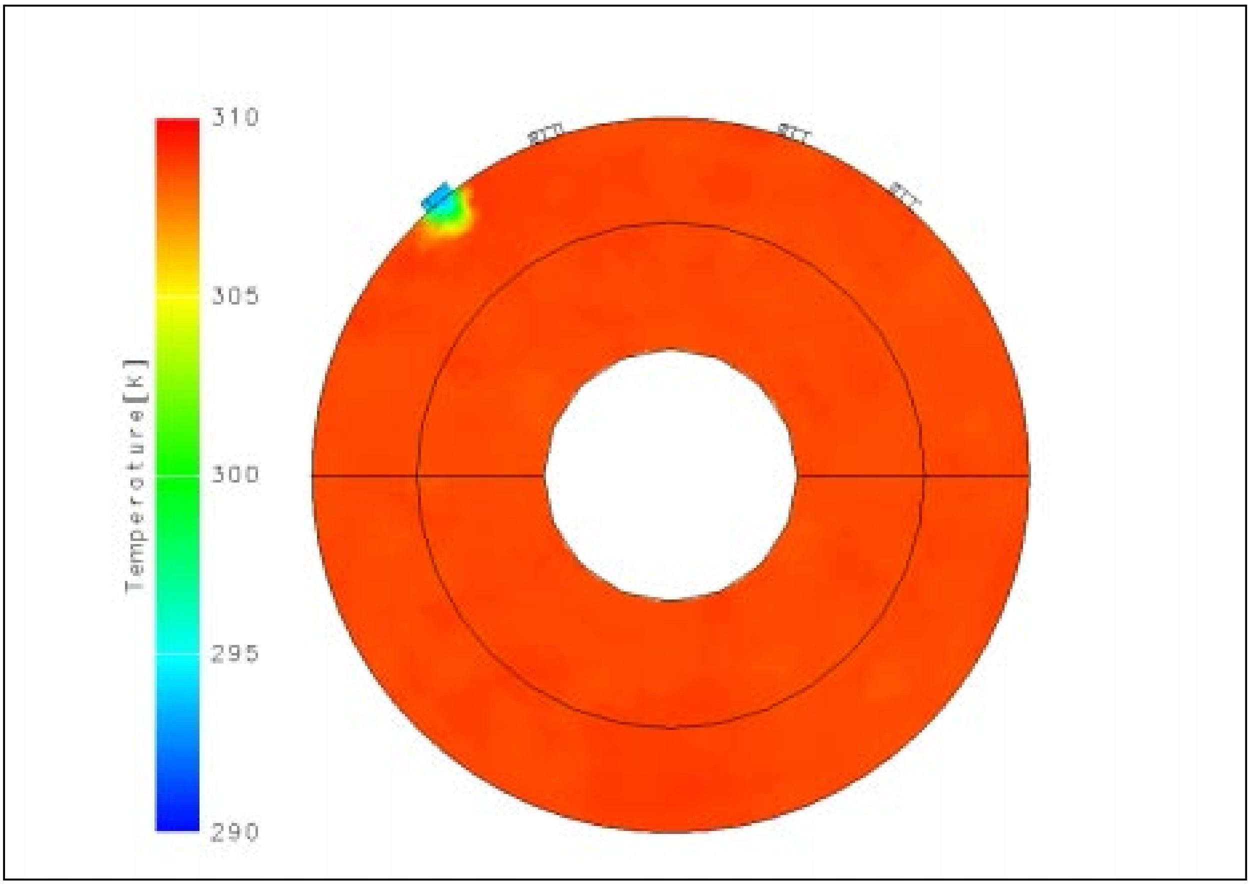

Figure 46: Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

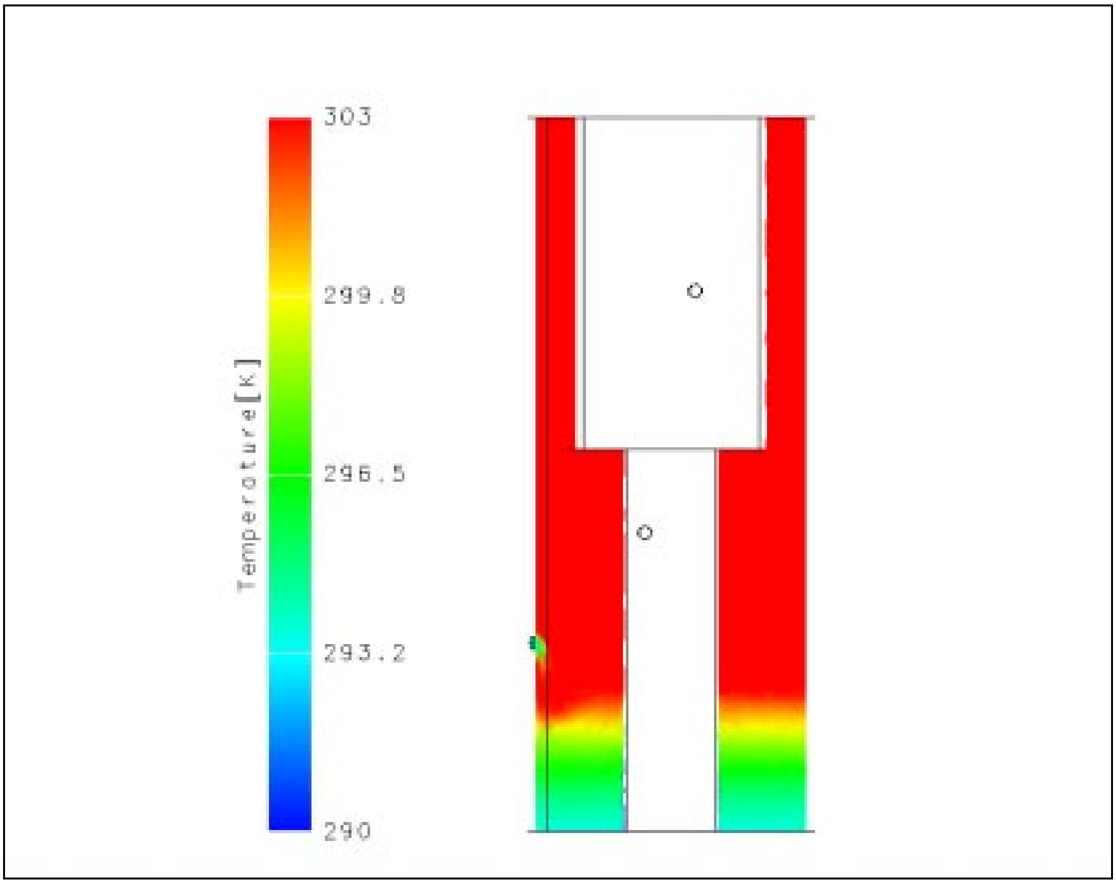

Figure 47: Calculated temperatures of the space heating water at a vertical section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

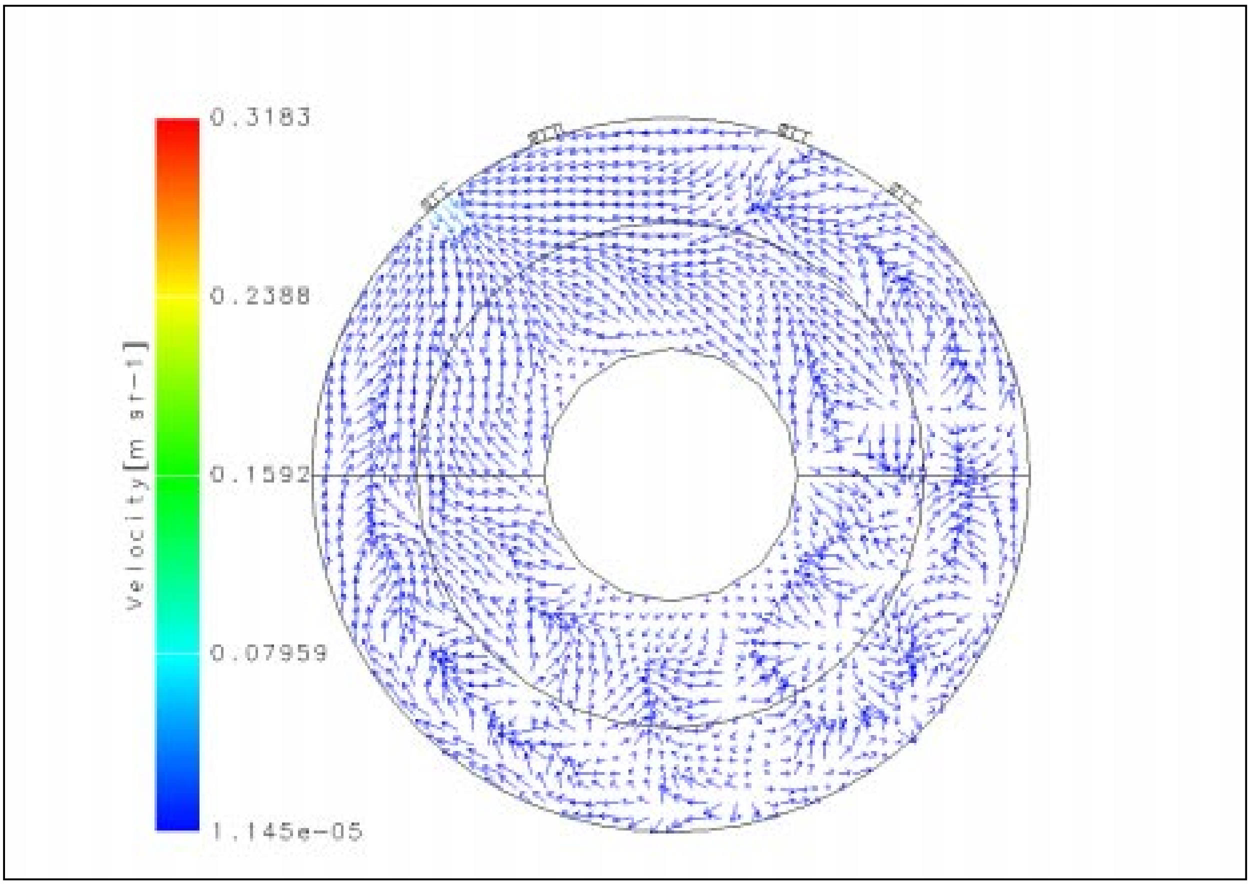

Figure 48: Vectors showing the flow in a horizontal section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only shows the direction of the flow. The range of colours indicates the velocity in [m/s].

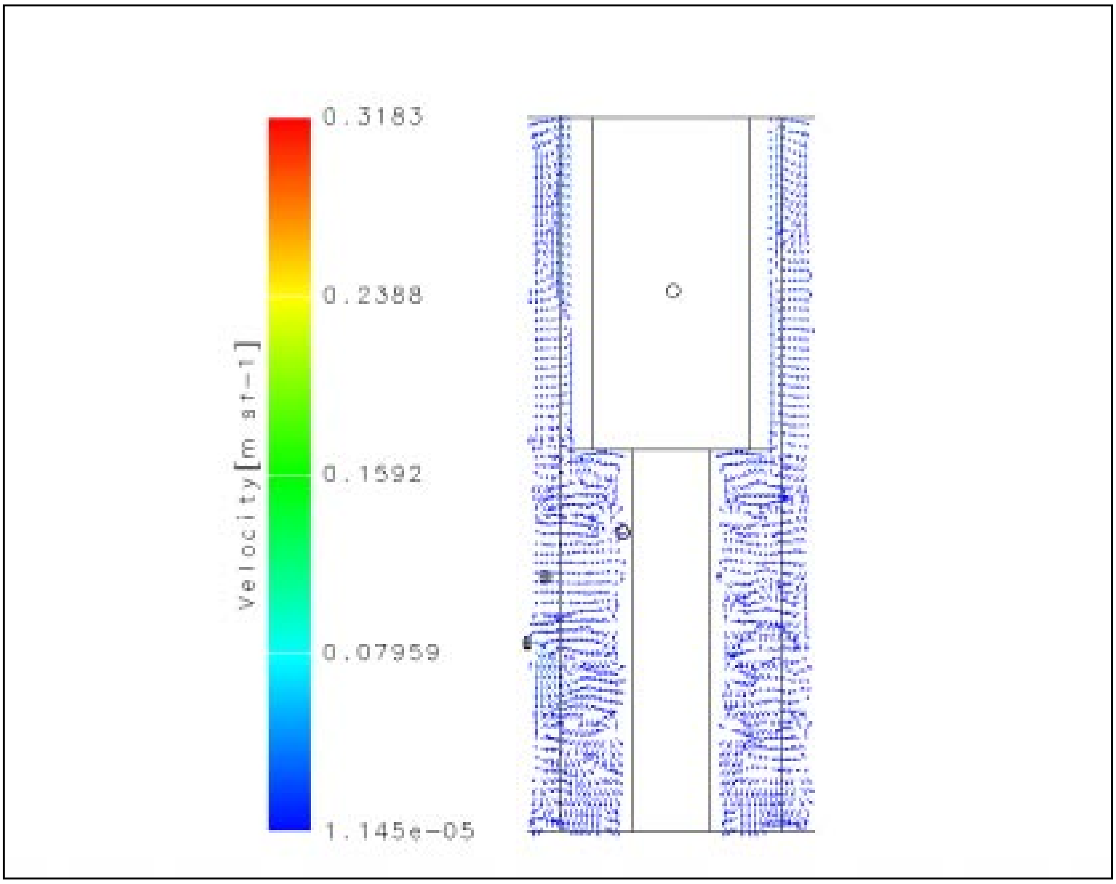

Figure 49: Vectors showing the flow in a vertical section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.5.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 50 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux on Figure 50 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that just like at operation condition 2a, the heat flux is largest on the upper part of the tank wall on a level with the inlet from the boiler loop. Further, it appears from Figure 50 that the heat transfer is small at the level between outlet to space heating and inlet from space heating which is due to the fact that the temperature difference between the outside of hot-water tank and water in the space heating storage tank is very small at this level. At this operation condition the total transferred power from the space heating storage tank to the hot-water tank is 1.6 kW/m² corresponding to 2.9 kW.

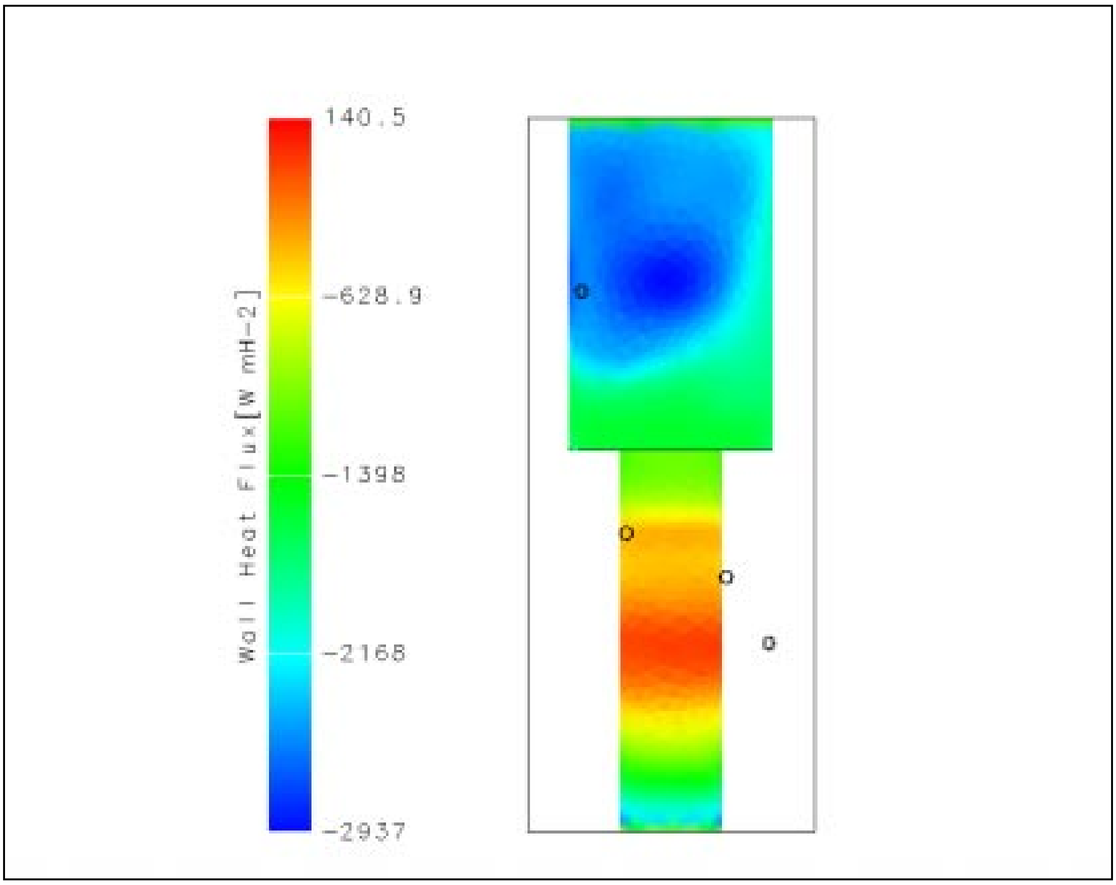

Figure 50: The calculated heat flux between space heating water and outside of hot-water tank at operation condition 2b. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 51 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 206 W/m²·K and 270 W/m²·K. At this operation condition, the average and total convective heat transfer coefficients are calculated to be 237 W/m²·K and 436 W/K, respectively.

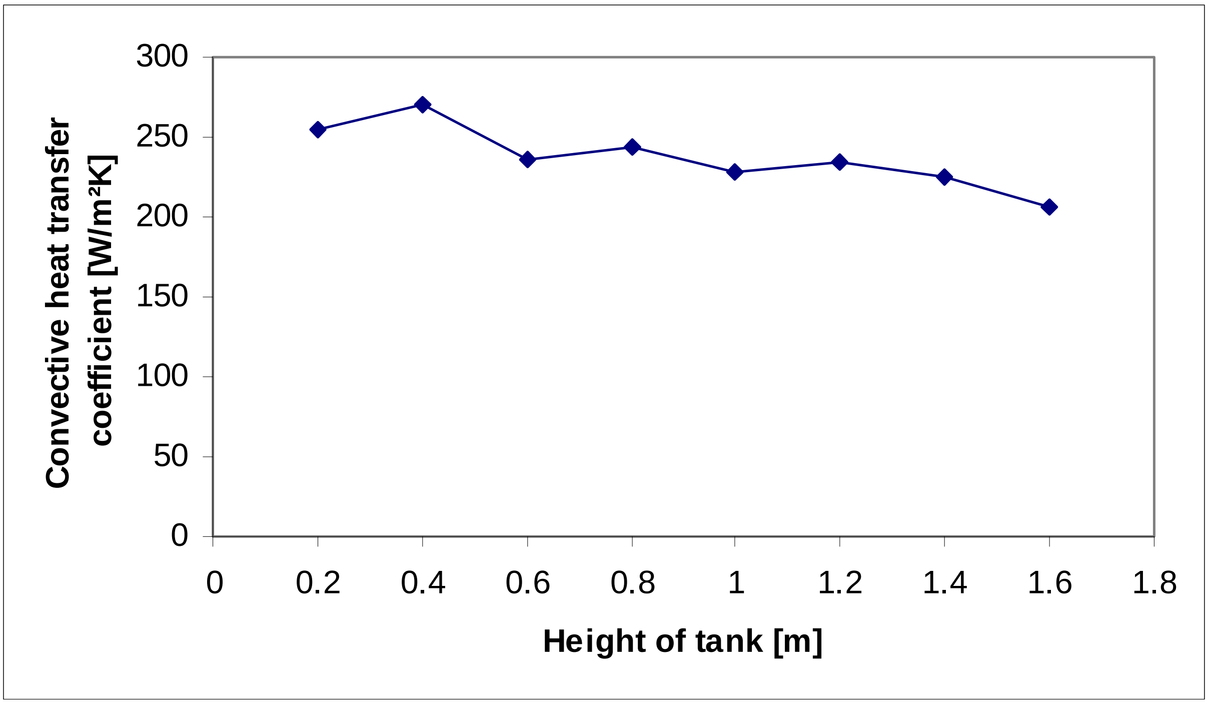

Figure 51: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 2b as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.6 Operation condition 2c

At operation condition 2c the starting temperatures given in Figure 6 are used. The boiler is not in operation. The space-heating loop is in operation at a flow of 1.4 l/min and an outlet temperature to the space heating storage tank of 20.5ºC.

Figure 52 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears that the power carried away to the space-heating loop results in a cooling of the middle part of the tank, whereas the temperature at the top of the tank remains unchanged, by and large.

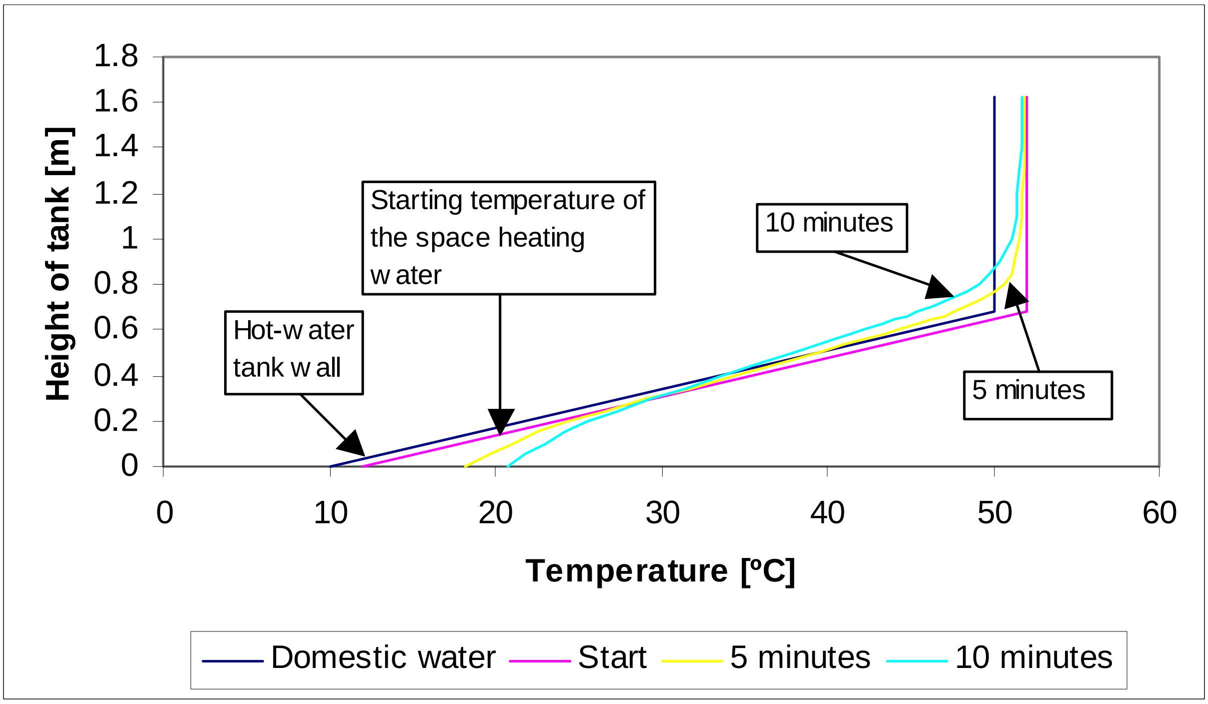

Figure 52: Calculated temperature in the space heating storage tank at start, after 5 minutes and after 10 minutes at operation condition 2c.

Figure 53 shows the calculated temperatures for inlet and outlet of the space-heating loop and the flow in the space-heating loop. Both temperatures and flows are shown as a function of the time. The inlet temperature from the space-heating loop to space heating storage tank and flow in the space-heating loop are constant at 20.5ºC and 1.4 l/min, respectively. The outlet temperature from space heating storage tank to space-heating loop falls from 51ºC to 46ºC. The power carried away to the space-heating loop falls from 2.9 kW to 2.4 kW during the 10 minutes in operation.

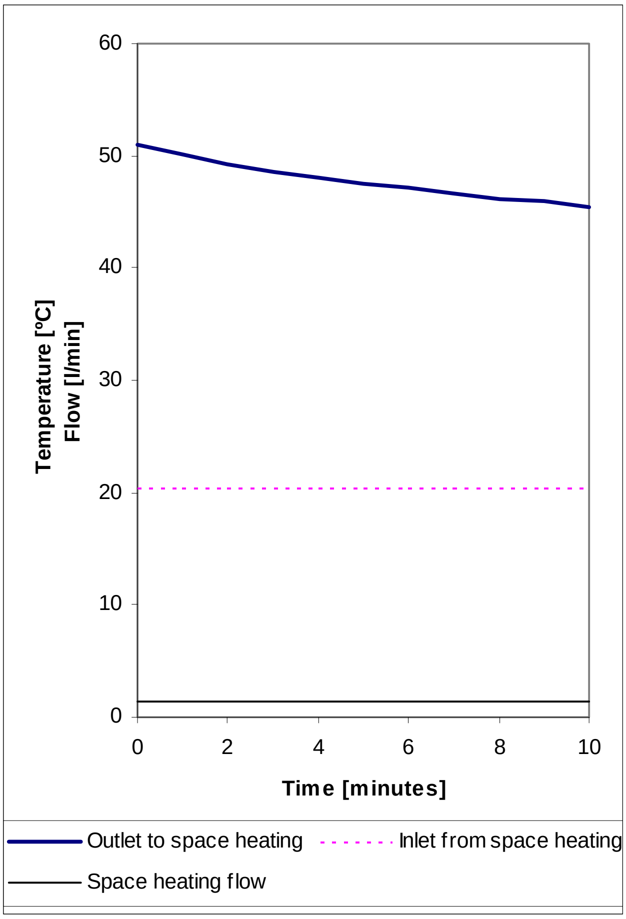

Figure 53: Inlet and outlet temperatures from space-heating loop and flow in space-heating loop as a function of the time for operation condition 2c. The power carried away to the space-heating loop is 2.4 kW after 10 minutes in operation.

3.6.1 Temperature and fluid motion around inlet and outlet

The boiler is not in operation at this operation condition. Therefore neither temperature nor fluid motion is shown around inlet and outlet from the boiler loop.

Figure 54 and Figure 55 show the temperature of the space heating water at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. Figure 56 and Figure 57 show the flows at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The size of the vectors in Figure 56 and Figure 57 does not show anything about the velocity, but only something about the direction. Figure 56 and Figure 57 show that on the whole the fluid motions around the inlet from the space-heating loop are identical to the conditions at operation condition 2b, which indicates that the boiler loop has no particular effect on these conditions.

Figure 58 shows the flows at a horizontal section through the outlet from the space heating storage tank to the space-heating loop. The size of the vectors in Figure 58 does not show anything about the volume of the flow, but only the direction of the flow. It appears that a great part of the motions in the water is directed towards the outlet to the space-heating loop. Unlike operation condition 1b (Figure 25) there is no downward flow close to the outside of the hot-water tank. This is owing to the fact that the boiler loop is not in operation at operation condition 2c, and that at operation condition 2c there is a en minimal temperature difference at this level between the outside of the hot-water tank and the space heating water.

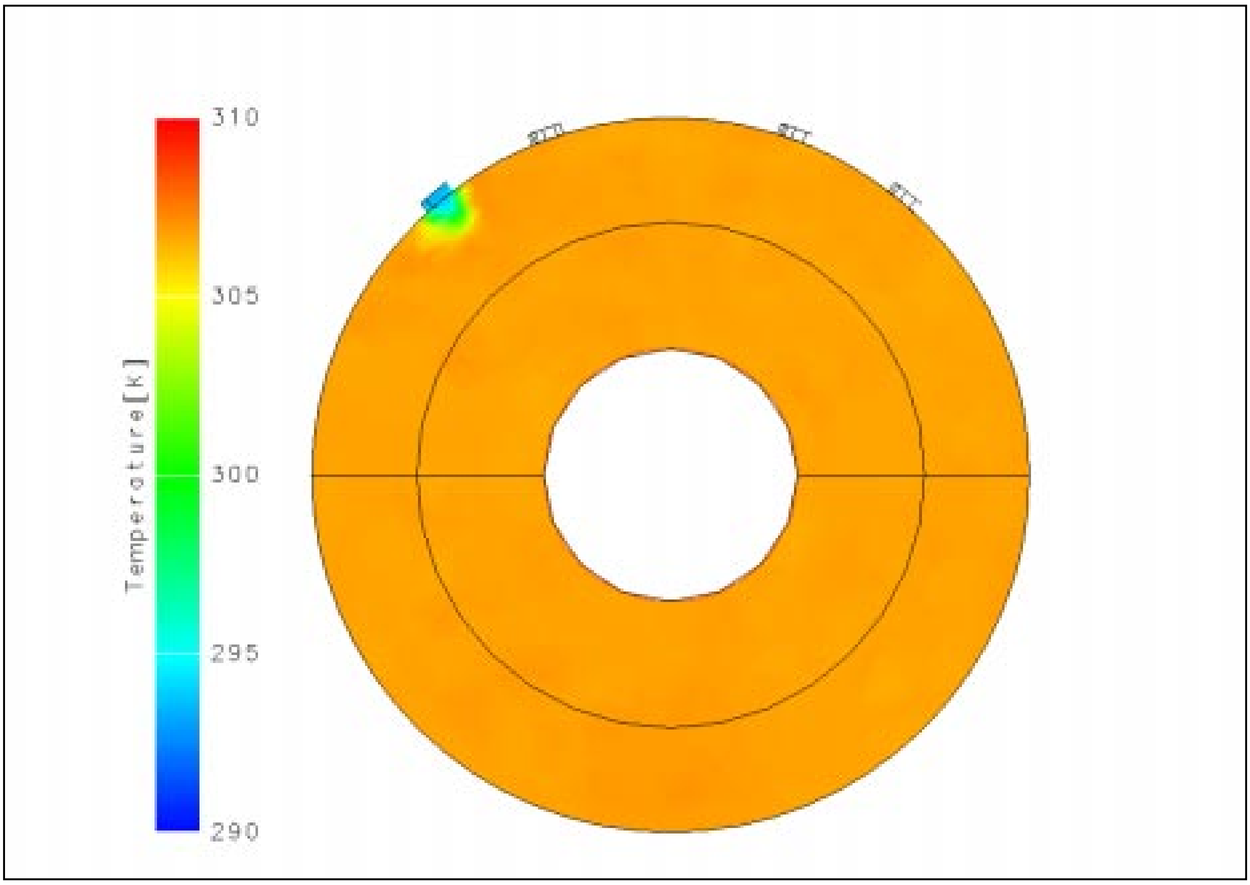

Figure 54: Calculated temperatures of the space heating water at et horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

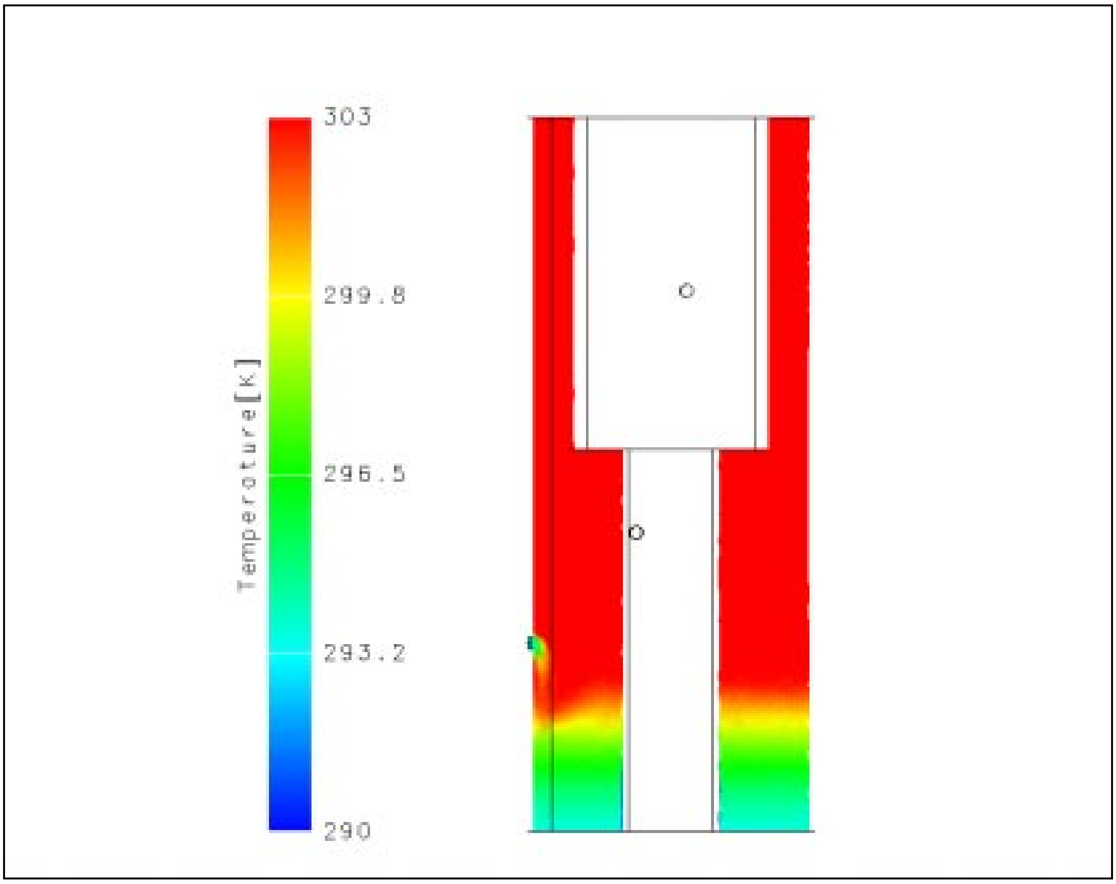

Figure 55: Calculated temperatures of the space heating water at et horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

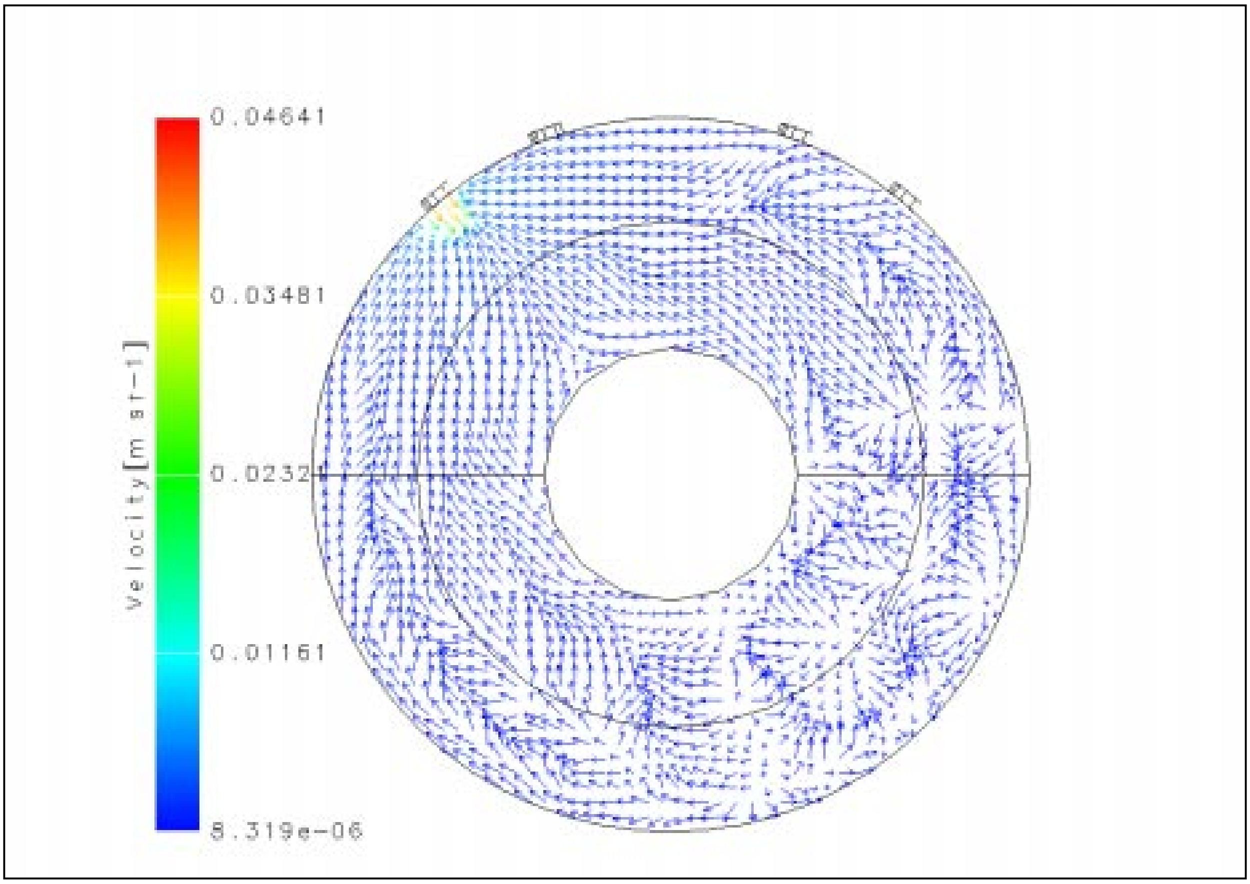

Figure 56: Vectors showing the flow in a horizontal section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

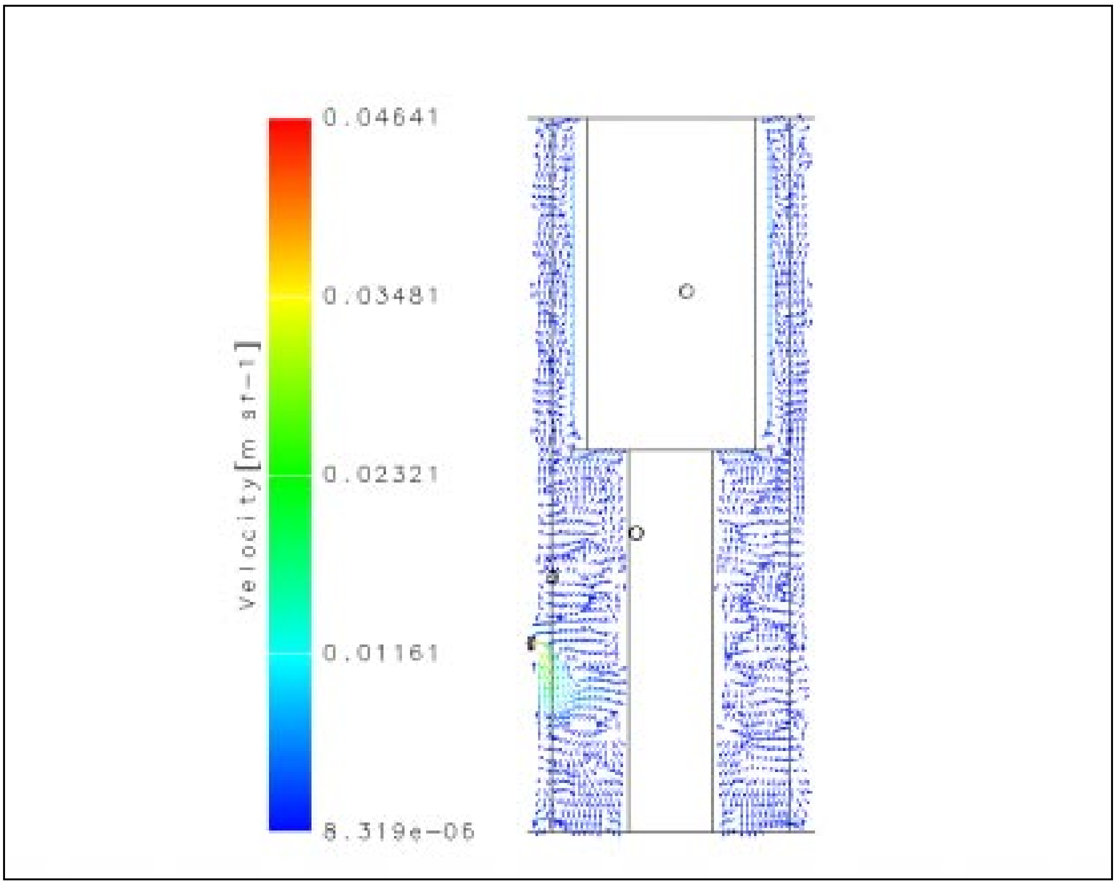

Figure 57: Vectors showing the flow in a vertical section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

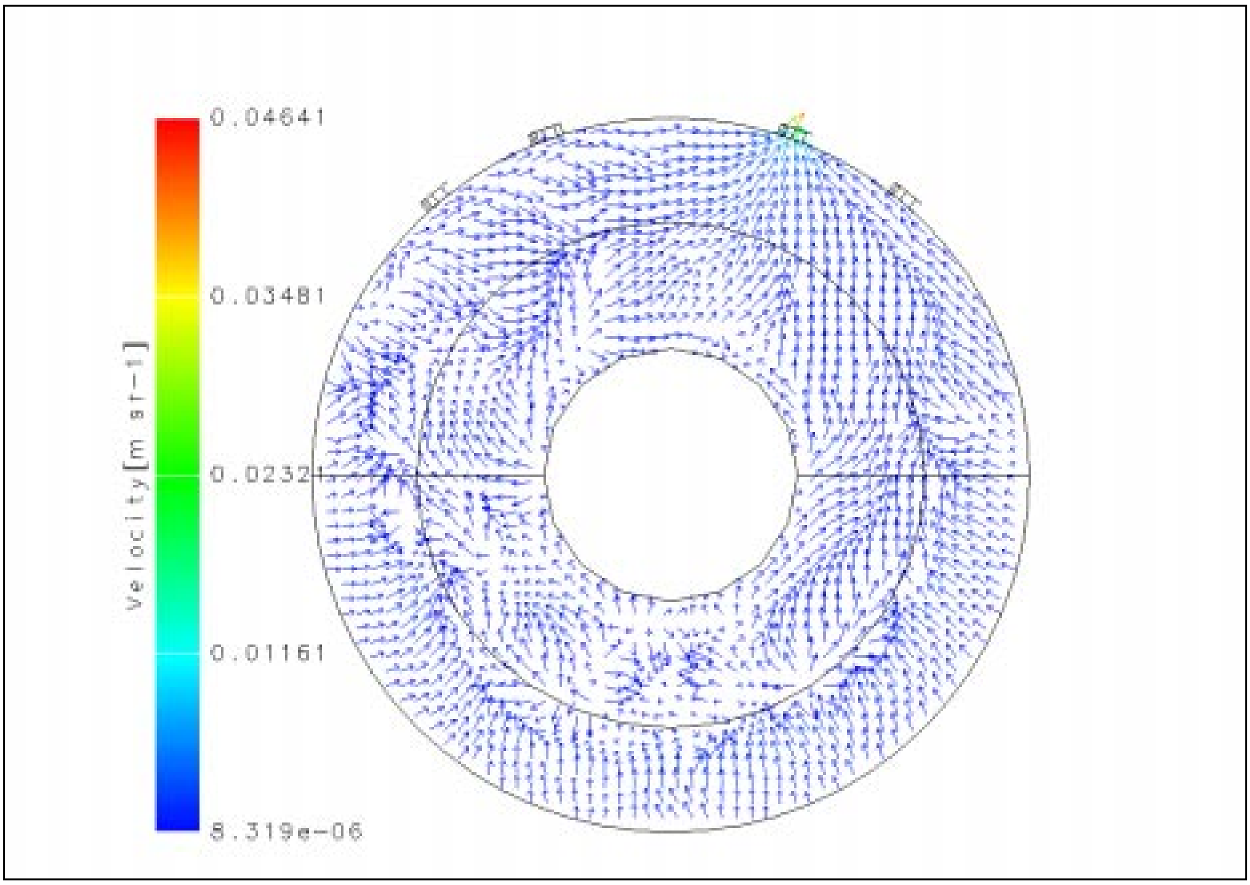

Figure 58: Vectors showing the flow in a horizontal section on a level with the outlet to the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.6.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 59 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux in Figure 59 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that just as at operation condition 2a, the heat flux is largest at the upper part of the tank wall on a level with the inlet from the boiler loop. Further, it appears from Figure 59 that on the level between outlet to space heating and inlet from space heating, heat is transferred to the space heating water from the hot-water tank. This is owing to the fact that at this level the temperature of the space heating water is lower than the outside of the hot-water tank. At this operation condition the total transferred power from the space heating storage tank to the hot-water tank is 0.2 kW/m² corresponding to 0.4 kW.

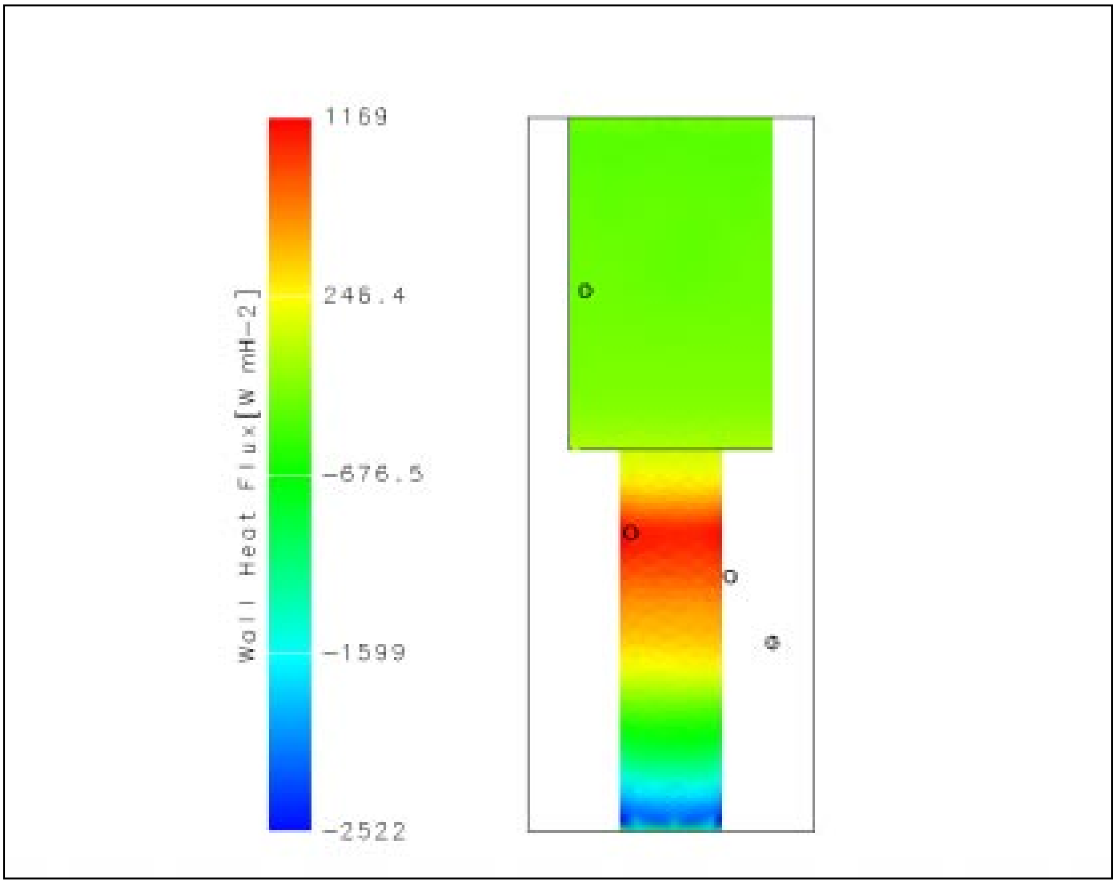

Figure 59: The calculated heat flux between space heating water and outside of hot-water tank at operation condition 2c. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 60 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 188 W/m²·K and 270 W/m²·K. It appears from Figure 60, however, that the convective heat transfer coefficient at the top of the tank falls, which is owing to the fact that the boiler loop is not in operation, and thus there is not very much motion in that part of the space heating storage tank. At this operation condition the average and total convective heat transfer coefficients are calculated at 222 W/m²·K and 409 W/K, respectively.

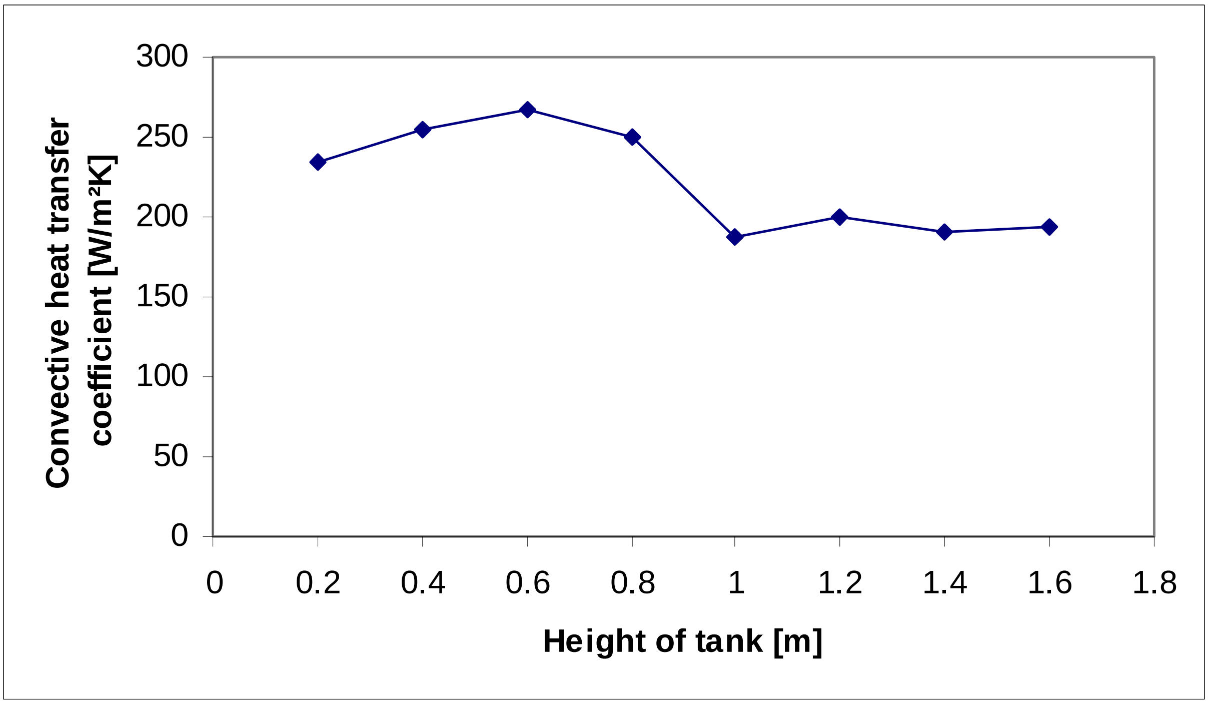

Figure 60: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 2c as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.7 Operation condition 2d

At operation condition 2d the starting temperatures given in Figure 6 are used. The boiler is not in operation. The space-heating loop is in operation with a flow of 1.4 l/min and an outlet temperature to the space heating storage tank of 30ºC.

Figure 61 shows the thermal stratification in the space heating storage tank at the start of the simulation, after 5 minutes, and after 10 minutes. It appears that the power carried away to the space-heating loop has the effect that the middle part of the tank is cooled, whereas the temperature at the top of the tank remains unchanged on the whole. Compared to operation condition 2c the outlet temperature from the space-heating loop has changed from 20.5ºC to 30ºC, but this change has a minimal effect on the thermal stratification in the space heating storage tank.

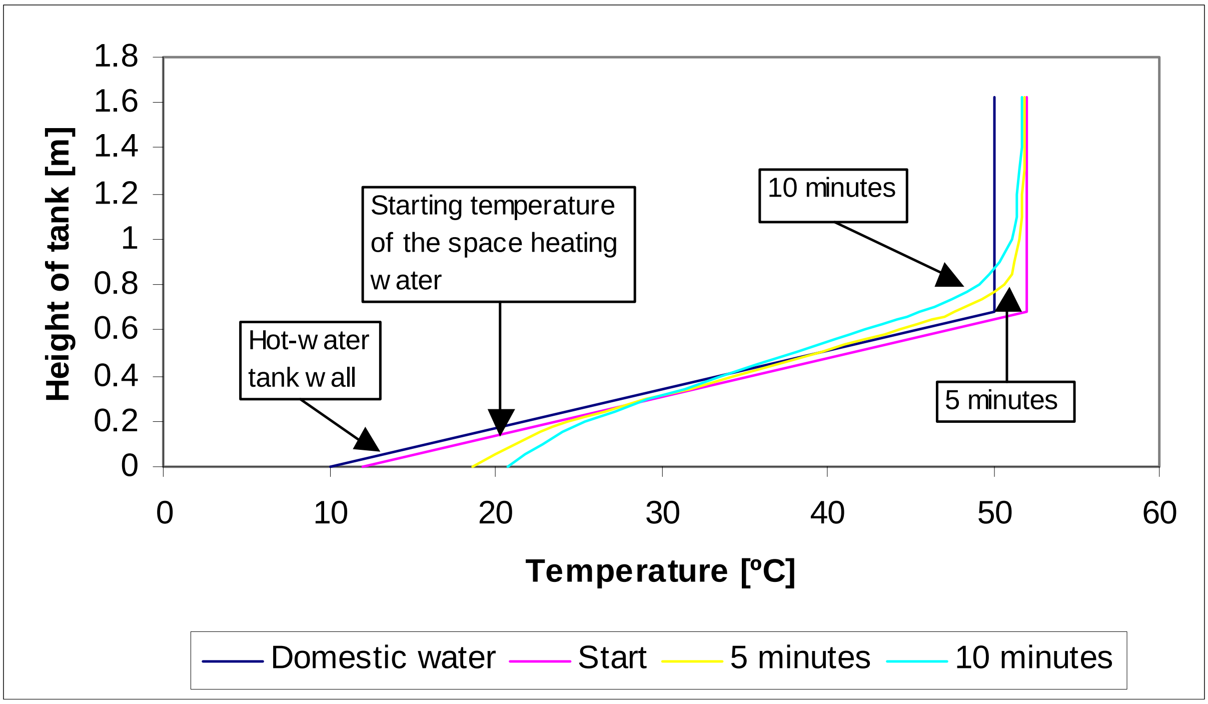

Figure 61: Calculated temperatures in he space heating storage tank at start, after 5 minutes, and after 10 minutes at operation condition 2d.

Figure 62 shows the calculated temperatures for inlet and outlet of the space-heating loop and the flow in the space-heating loop. Both temperatures and flows are shown as a function of the time. The inlet temperature from the space-heating loop to space heating storage tank and flow in the space-heating loop are constant at 30ºC and 1.4 l/min, respectively. The outlet temperature from space heating storage tank to space-heating loop falls from 51ºC to 46ºC. During the 10 minutes in operation the power carried away to the space-heating loop falls from 2.0 kW to 1.5 kW.

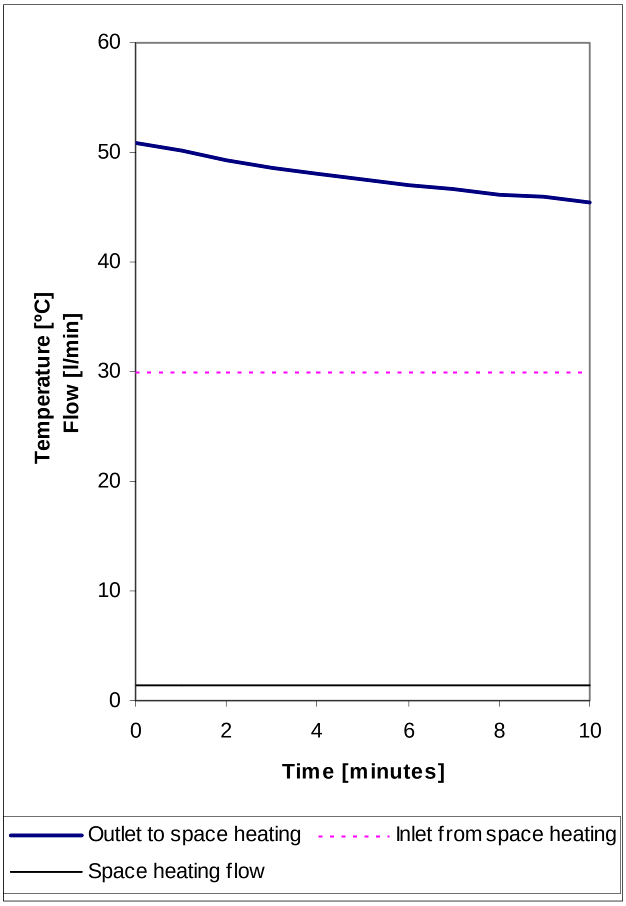

Figure 62: Inlet and outlet temperatures from space-heating loop and flow in space-heating loop as a function of the time for operation condition 2d. After 10 minutes in operation the power carried away to the space-heating loop is 1.5 kW.

3.7.1 Temperature and fluid motion around inlet and outlet

The boiler is not in operation at this operation condition. Therefore neither temperature nor fluid motion is shown around inlet and outlet from the boiler loop.

Figure 63 and Figure 64 show the temperature of the space heating water at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. Figure 65 and Figure 66 show the flows at a horizontal and a vertical section, respectively, through the inlet from the space-heating loop. The size of the vectors in Figure 65 and Figure 66 does not show anything about the velocity, but only something about the direction. Figure 65 and Figure 66 show how the flow around the inlet changes when the inlet temperature changes from 20.5ºC to 30ºC. As the temperature of the space heating water at the same level as the inlet is approximately 35ºC, there is a small temperature difference between the water in the tank and the in-coming water from the space-heating loop. The result is that some of the in-coming water continues and hits the outside of the hot-water tank. Some of the in-coming water flows downwards in the tank, too, but it does not get as far down as at the other operation conditions. Further, it appears from Figure 65 that recirculation is formed on each side of the inlet flow on the horizontal level.

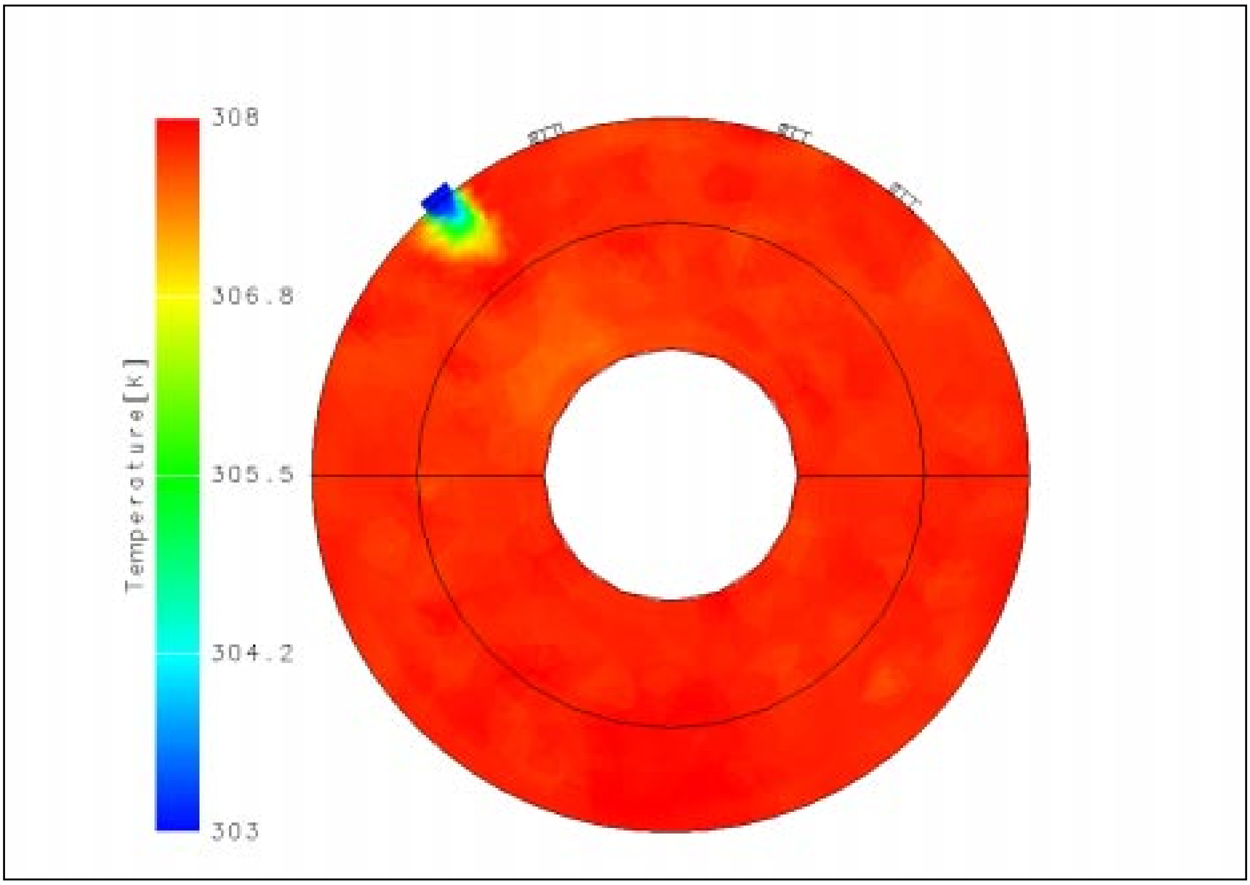

Figure 63: Calculated temperatures of the space heating water at a horizontal section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

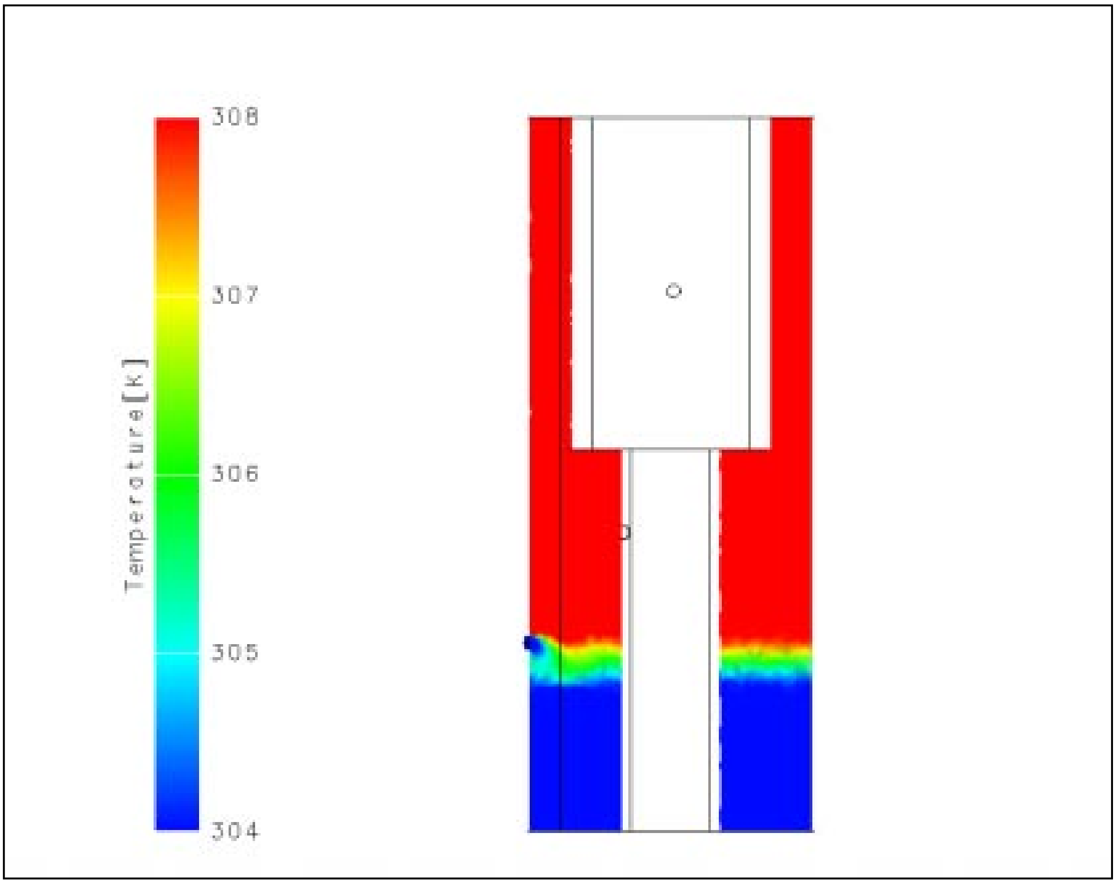

Figure 64: Calculated temperatures of the space heating water at a vertical section on a level with the inlet from the space-heating loop (after 10 minutes' heating). The range of colours indicates the temperatures in [K].

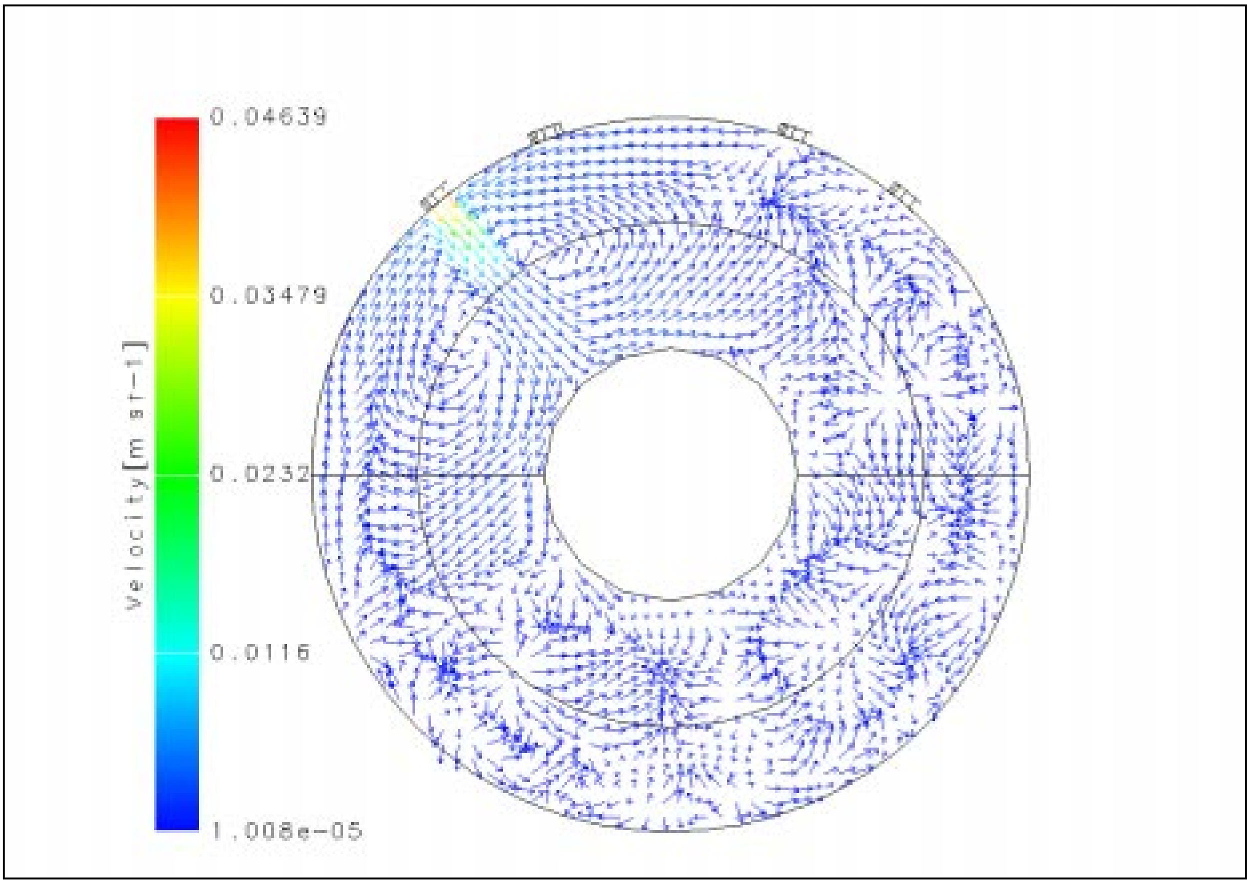

Figure 65: Vectors showing the flow in a horizontal section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

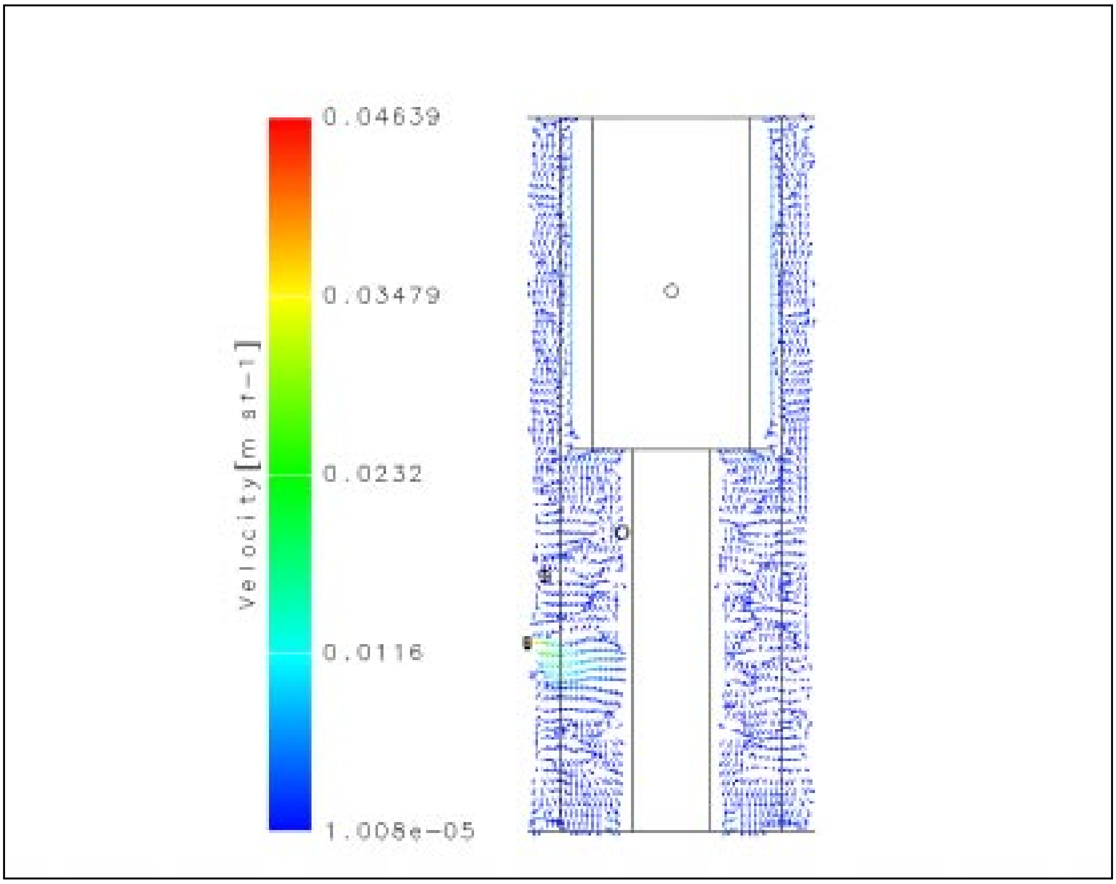

Figure 66: Vectors showing the flow in a vertical section on a level with the inlet from the space-heating loop. The size of the vectors does not show anything about the velocity rate, but only the direction of the flow. The range of colours indicates the velocity in [m/s].

3.7.2 Heat transfer at hot-water tank

The CFD-program calculates the heat transfer between water in the space heating storage tank and the tank wall against the domestic water, whereas the convective heat transfer coefficient between water in the space heating storage tank and the tank wall against domestic water (i.e. the outside of the hot-water tank wall) is calculated by equation (2).

Figure 67 shows the calculated heat flux between the water in the space heating storage tank and the tank wall against the domestic water. A negative heat flux on Figure 67 means that the heat is transferred from space heating water to tank wall against domestic water. It appears that just as at operation condition 2a, the heat flux is largest at the upper part of the tank wall on a level with the inlet from the boiler loop. Further, it appears from Figure 67, that on the level between outlet to space heating and inlet from space heating, heat is transferred to the space heating water from the hot-water tank. This is owing to the fact that at this level the temperature of the space heating water is lower than the outside of the hot-water tank. At this operation condition the total transferred power from the space heating storage tank to the hot-water tank is 0.2 kW/m² corresponding to 0.4 kW.

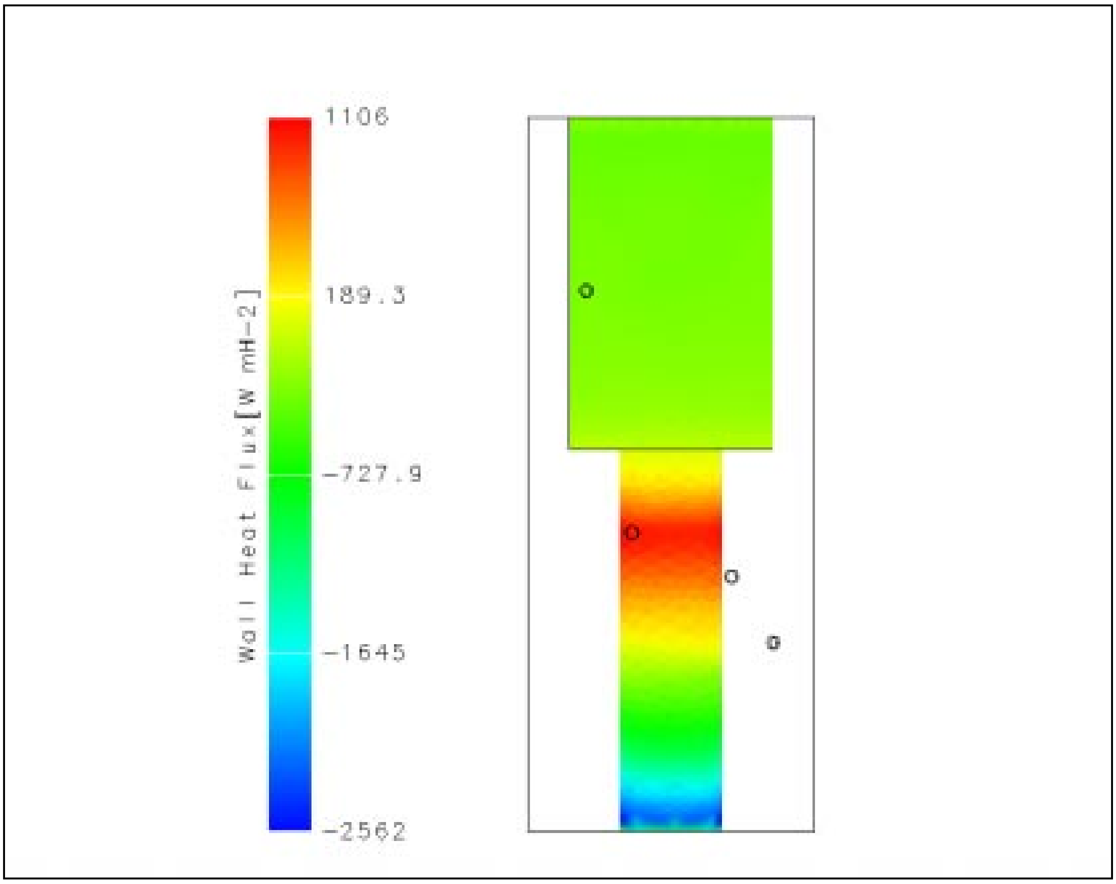

Figure 67: The calculated heat flux between space heating water and outside of hot-water tank at operation condition 2d. The range of colours indicates the heat flux in [W/m²]. A negative heat flux indicates that the heat is transferred from space heating water to hot-water tank wall.

Figure 68 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. The convective heat transfer coefficient varies between 191 W/m²·K and 270 W/m²·K. It appears from F65, however, that the convective heat transfer coefficient at the top of the tank falls, which is owing to the fact that the boiler loop is not in operation, and thus there is not very much motion in that part of the space heating storage tank. At this operation condition the average and total convective heat transfer coefficient are calculated at 223 W/m²·K and 410 W/K, respectively.

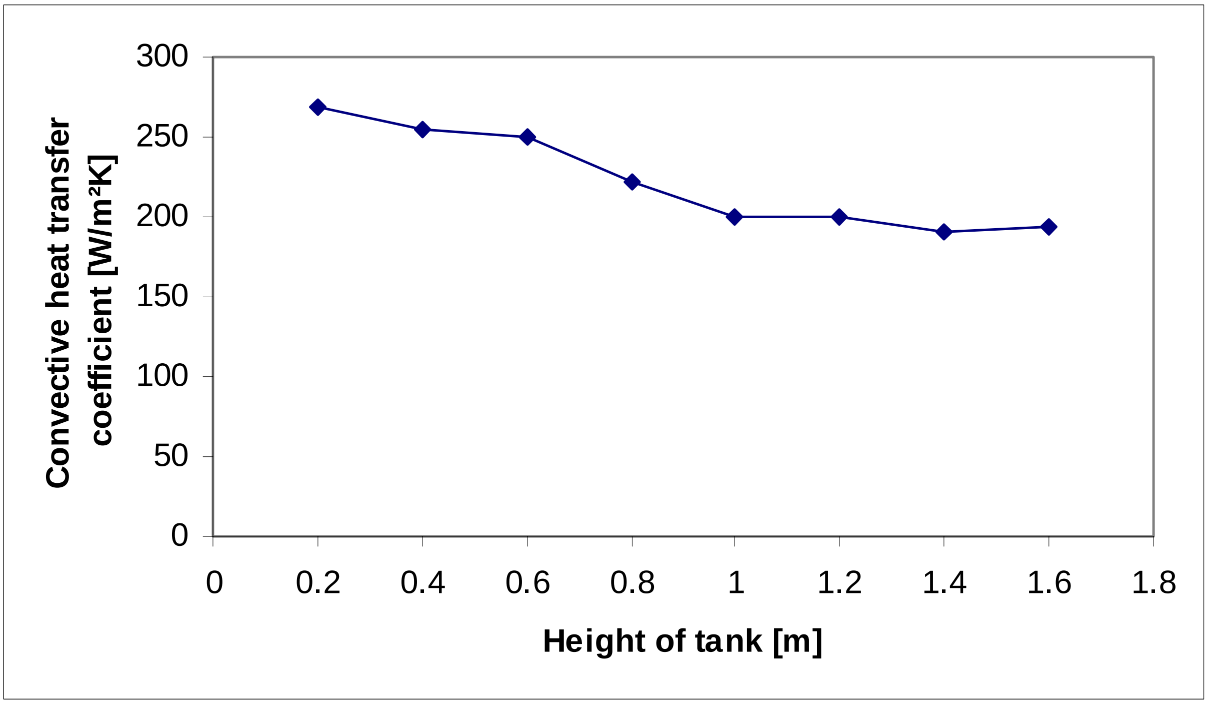

Figure 68: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 2d as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

3.8 Heat transfer in hot-water tank at stagnation in tank

In the preceding parts the convective heat transfer coefficient between space heating water and the outside of the hot-water tank has been explained for operation conditions 1a-2d, where either the boiler loop or the space-heating loop or both parts are in operation. The convective heat transfer coefficient has also been investigated at operation conditions where neither boiler loop nor space-heating loop is in operation. The convective heat transfer coefficient has been investigated both in a situation with a large temperature difference between water in the space heating storage tank and the outside of the hot-water tank (operation condition 1), and in a situation with a small temperature difference (operation condition 2). The two operation conditions are called 1d and 2e, respectively.

3.8.1 Operation condition 1d

At this investigation the starting temperatures in Figure 5, are used and neither boiler nor space-heating loop is in operation. Figure 69 shows the thermal stratification at the start of the simulation and after 10 minutes. It appears that the space heating water at the top of the tank are cooled, whereas the temperature rises a little in a small area in the middle of the tank.

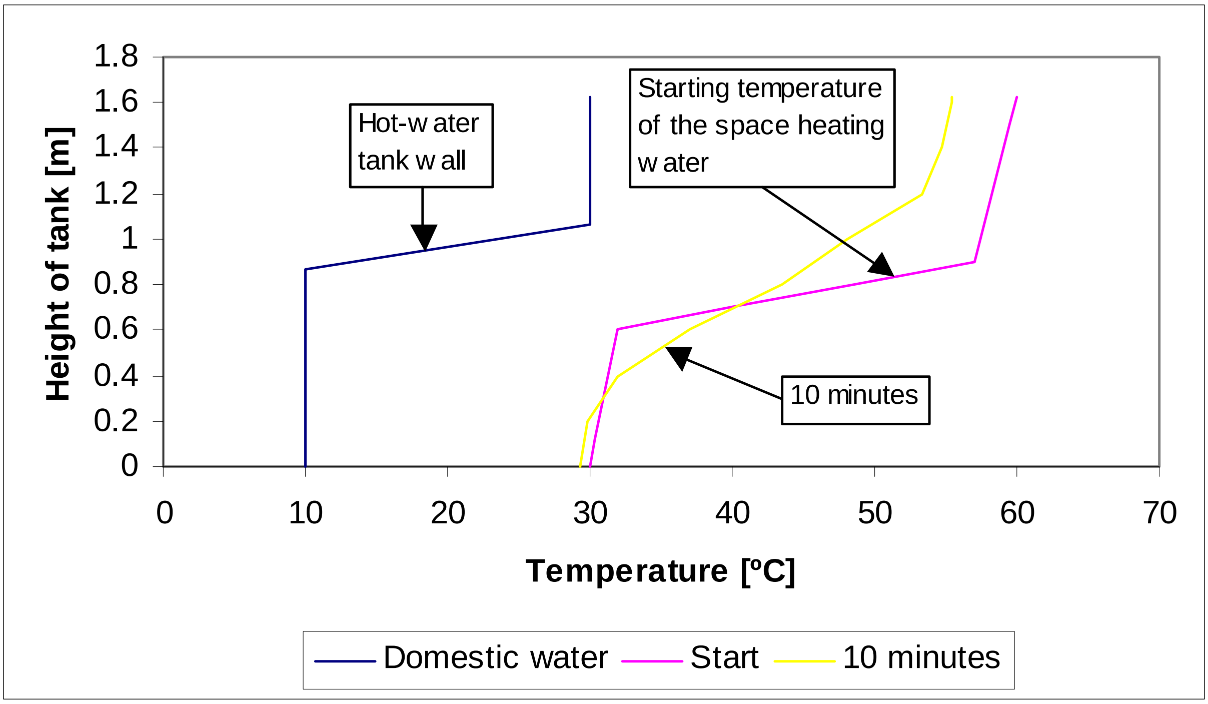

Figure 69: Calculated temperatures in the space heating storage tank at start and after 10 minutes at operation condition 1d.

Figure 70 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. It appears that the convective heat transfer coefficient is very small, and it varies between 24 W/m²·K and 28 W/m²·K. At this operation condition the average and total convective heat transfer coefficients are calculated at 26 W/m²·K and 47 W/K, respectively.

The calculated convective heat transfer coefficients in Figure 70 are calculated by equation (2), which, among other things, is based on the mean temperature of the space heating water at the respective height levels. At operation condition 1d the motions of the water in the tank are very small, and that means that the boundary layer close to the hot-water tank becomes thicker than at operation conditions 1a-1c. The thickness of the boundary layer has an effect on the mean temperature in the respective height levels, and therefore the mean temperature of the space heating water in the respective height levels is, to a higher degree than at operation conditions 1a-1c, dependent on the difference in diameter between the outside of the hot-water tank and the inside of the space heating storage tank. This has the effect that the calculated convective heat transfer coefficients in Figure 70 are more sensitive to a change of tank diameter than the calculated convective heat transfer coefficients at operation conditions 1a-1c.

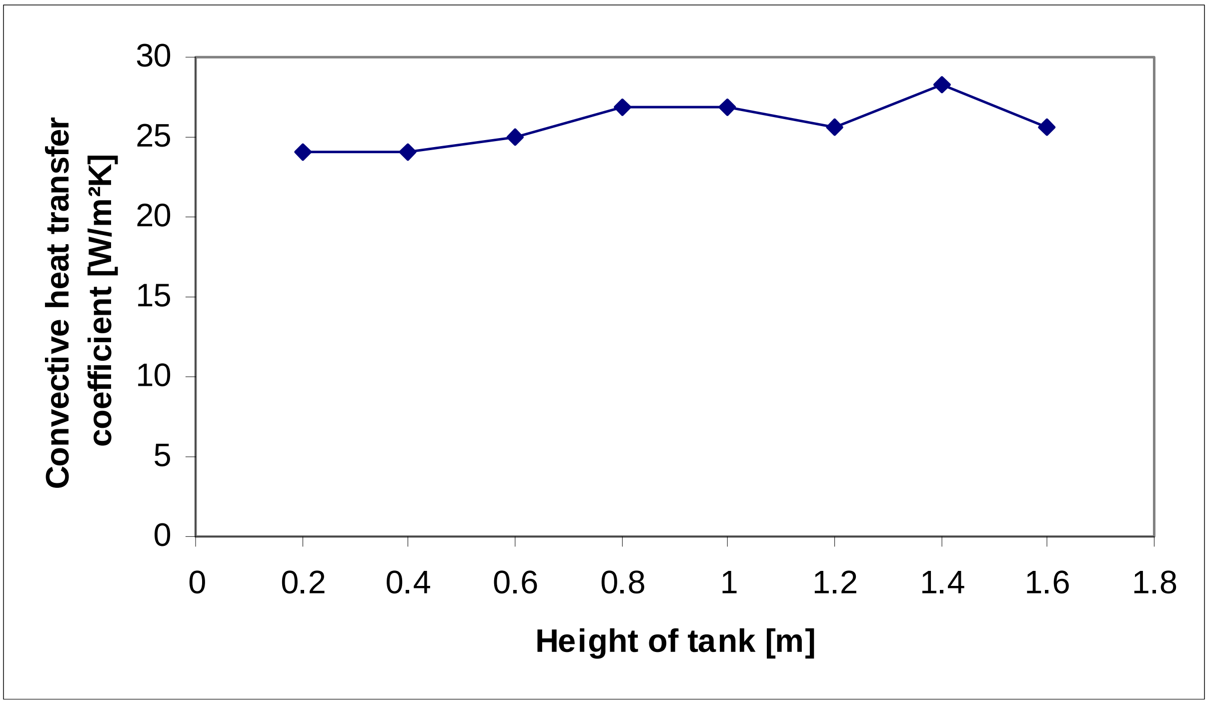

Figure 70: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 1d as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

At the start in all the simulations in CFX the water in the space heating storage tank is totally at rest. At operation conditions 1a-1c the water quickly gets into motion, as boiler loop and space-heating loop are in operation. At operation condition 1d, however, where the motions of the water are only controlled by temperature differences, the water gets into motion somewhat slower. To investigate the convective heat transfer coefficient in a situation where the space heating water is in motion, but neither boiler loop nor space-heating loop is in operation, the simulation of operation condition 1b continued for 10 minutes with boiler loop and space-heating loop not in operation.

Figure 71 shows the thermal stratification in the space heating storage tank 0.5 minute, 1 minute, 2 minutes, 5 minutes, and 10 minutes, respectively, after the boiler loop and space-heating loop have stopped. The space heating water is slowly cooling, especially in the top. Figure 72 shows how the convective heat transfer coefficient change in the course of time. It appears that the convective heat transfer coefficient slowly falls, but it is much greater than in Figure 70, as the water in the space heating storage tank is in motion.

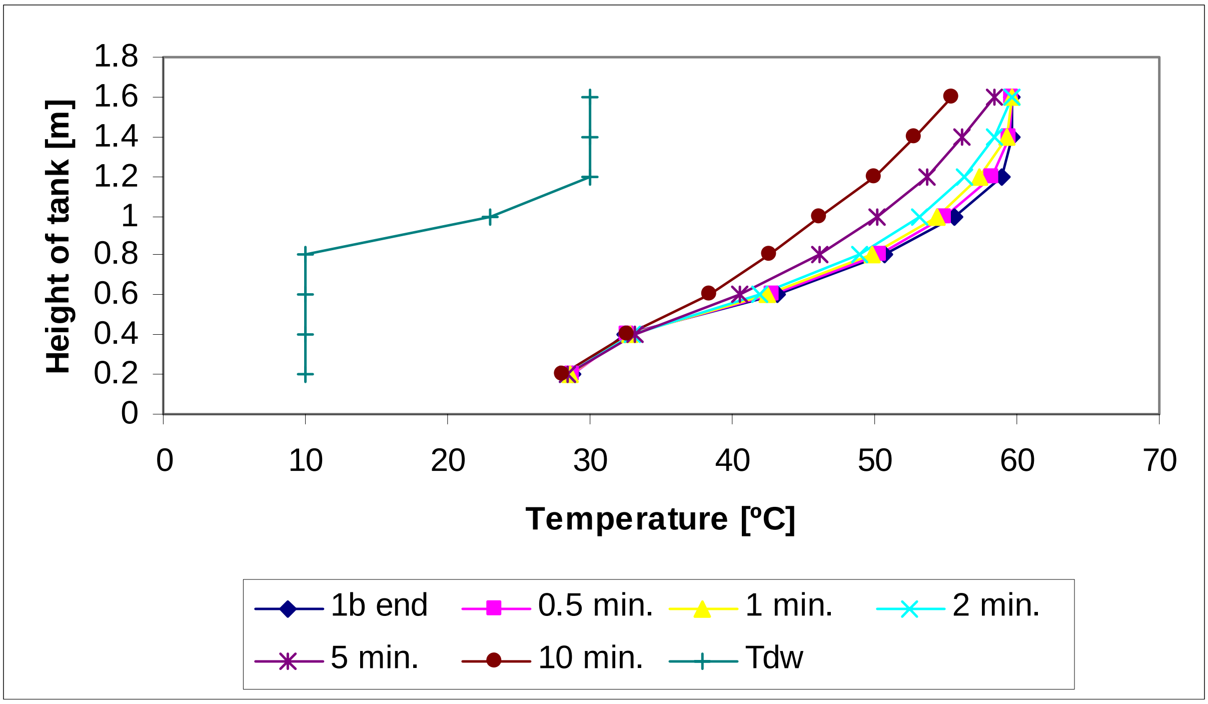

Figure 71: Calculated temperatures in the space heating storage tank after stop for boiler loop and space-heating loop after operation condition 1b.

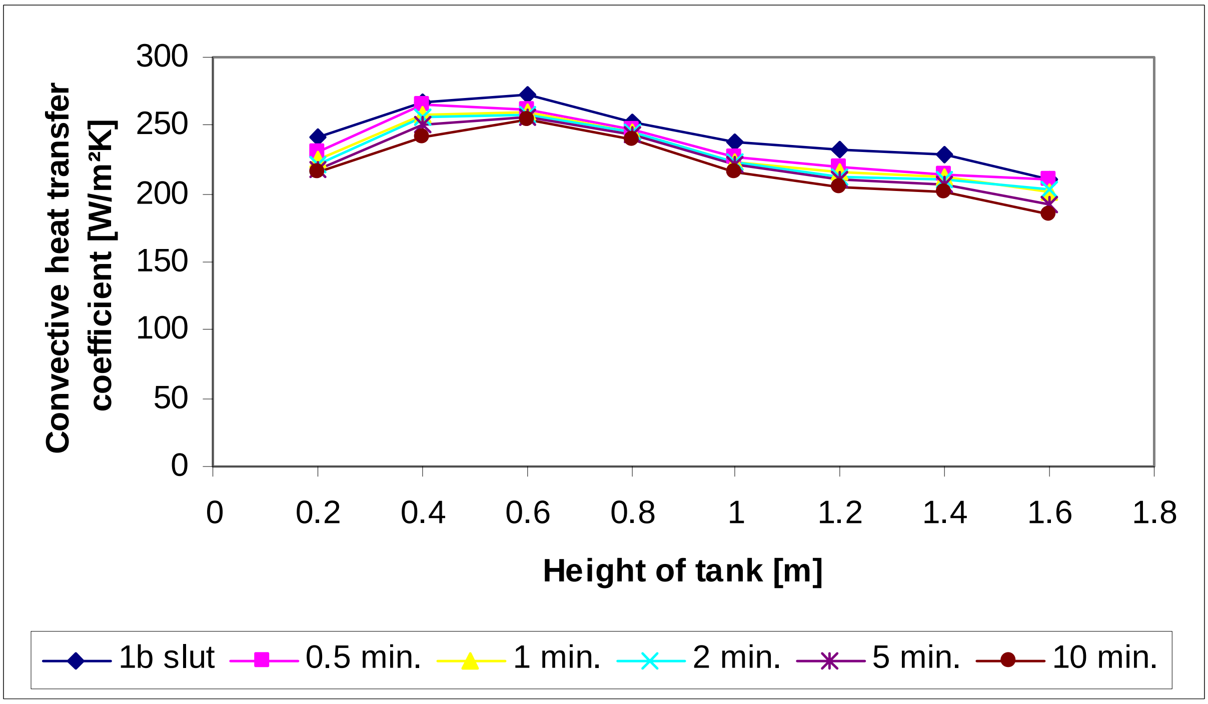

Figure 72: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall after stop for boiler loop and space-heating loop after operation condition 1b.

3.8.2 Operation condition 2e

At this investigation the starting temperatures in Figure 6, are used, and neither boiler nor space-heating loop is in operation. Figure 73 shows the thermal stratification at the start of the simulation and after 10 minutes. It appears that the space heating water at the top of the tank is only cooled a little, whereas the temperature falls a little more in the middle part of the tank.

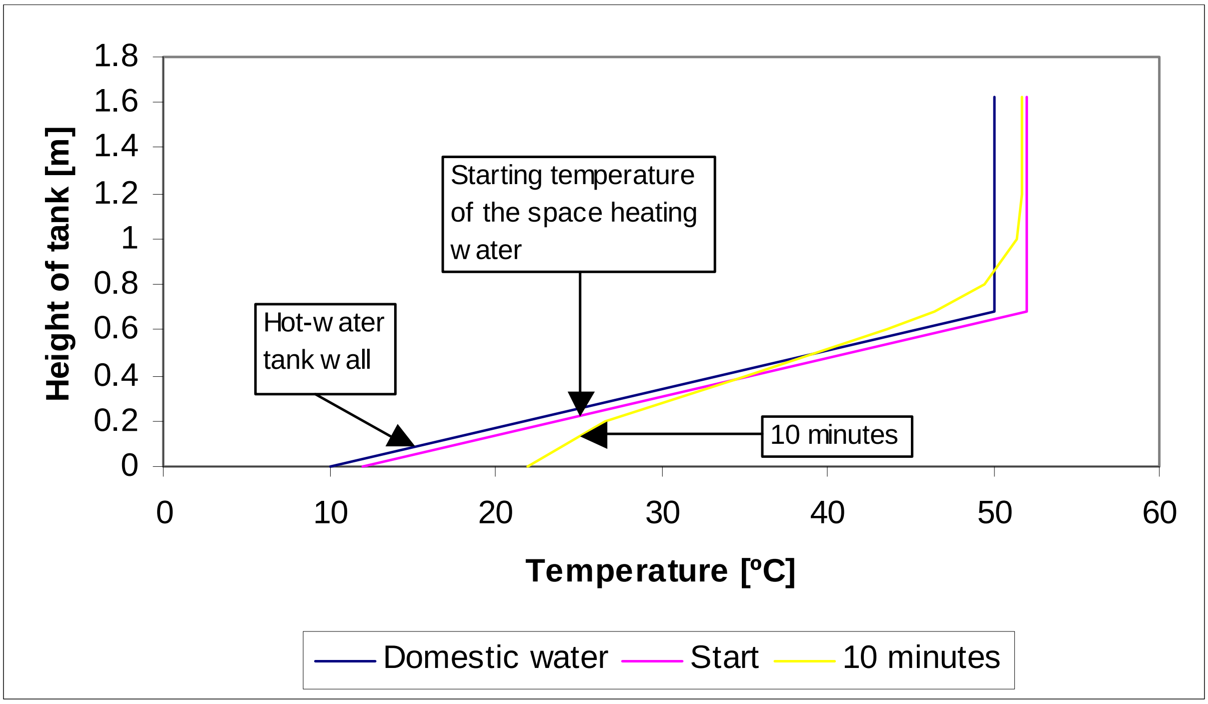

Figure 73: Calculated temperatures in the space heating storage tank at start and after 10 minutes at operation condition 2e.

Figure 74 shows the calculated convective heat transfer coefficient from the water in the space heating storage tank to the hot-water tank wall as a function of the height. It appears that the convective heat transfer coefficient is very small, and it varies between 23 W/m²·K and 29 W/m²·K. At this operation condition the average and total convective heat transfer coefficients, respectively, are calculated at 26 W/m²·K and 48 W/K, respectively.

The calculated convective heat transfer coefficients in Figure 74 are calculated by equation (2), which, among other things, are based on the mean temperature of the space heating water in the respective height levels. At operation condition 2e the motions of the water in the tank are very small, and that means that the boundary layer close to the hot-water tank becomes thicker than at operation conditions 2a-2d. The thickness of the boundary layer has an effect on the mean temperature in the respective height levels, and therefore the mean temperature of the space heating water in the respective height levels is to a greater extent than at operation conditions 2a-2d dependent on the difference in diameter between the outside of the hot-water tank and the inside of the space heating storage tank. The result is that the calculated convective heat transfer coefficients in Figure 74 are more sensitive to a change of tank diameter than the calculated convective heat transfer coefficients at operation conditions 2a-2d. As, on the whole, the calculated convective heat transfer coefficients at operation condition 2e are identical to the calculated convective heat transfer coefficients at operation condition 1d, this means that the convective heat transfer coefficient at a stagnation in the tank is, by and large, independent of the temperature difference between space heating water and hot-water tank wall.

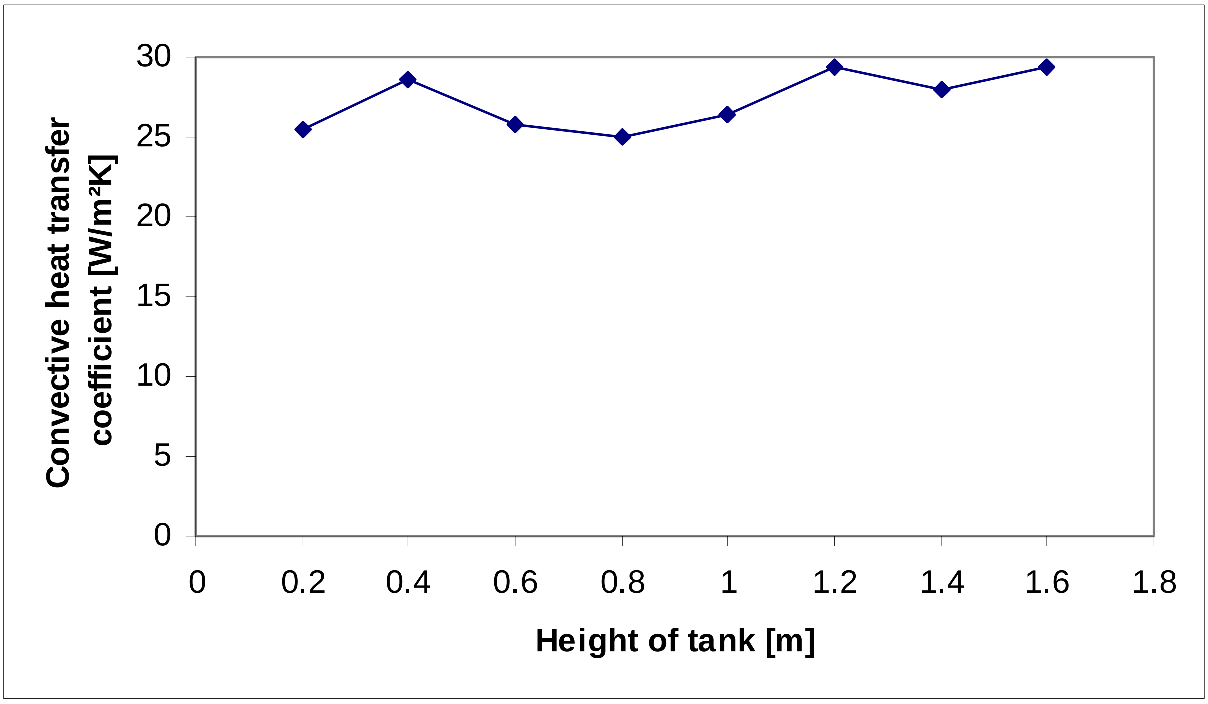

Figure 74: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall at operation condition 2e as a function of the height. The convective heat transfer coefficient is calculated by equation (2).

At the start in all the simulations in CFX the water in the space heating storage tank is totally at rest. At operation condition 2a-2d the water quickly gets into motion, as boiler loop and space-heating loop are in operation. At operation condition 2e, however, where the motions of the water are only controlled by temperature differences, the water gets into motion somewhat slower. To investigate the convective heat transfer coefficient in a situation where the space heating water is in motion, but neither boiler loop nor space-heating loop is in operation, the simulation of operation condition 2b continued for 10 minutes with boiler loop and space-heating loop not in operation.

Figure 75 shows the thermal stratification in the space heating storage tank 0.5 minute, 1 minute, 2 minutes, 5 minutes and 10 minutes, respectively, after the boiler loop and space-heating loop have stopped. The space heating water is slowly cooling, especially in the top. Figure 76 shows how the convective heat transfer coefficient change in the course of time. It appears that the convective heat transfer coefficient slowly falls, but it is much greater than in Figure 74, as the water in the space heating storage tank is in motion.

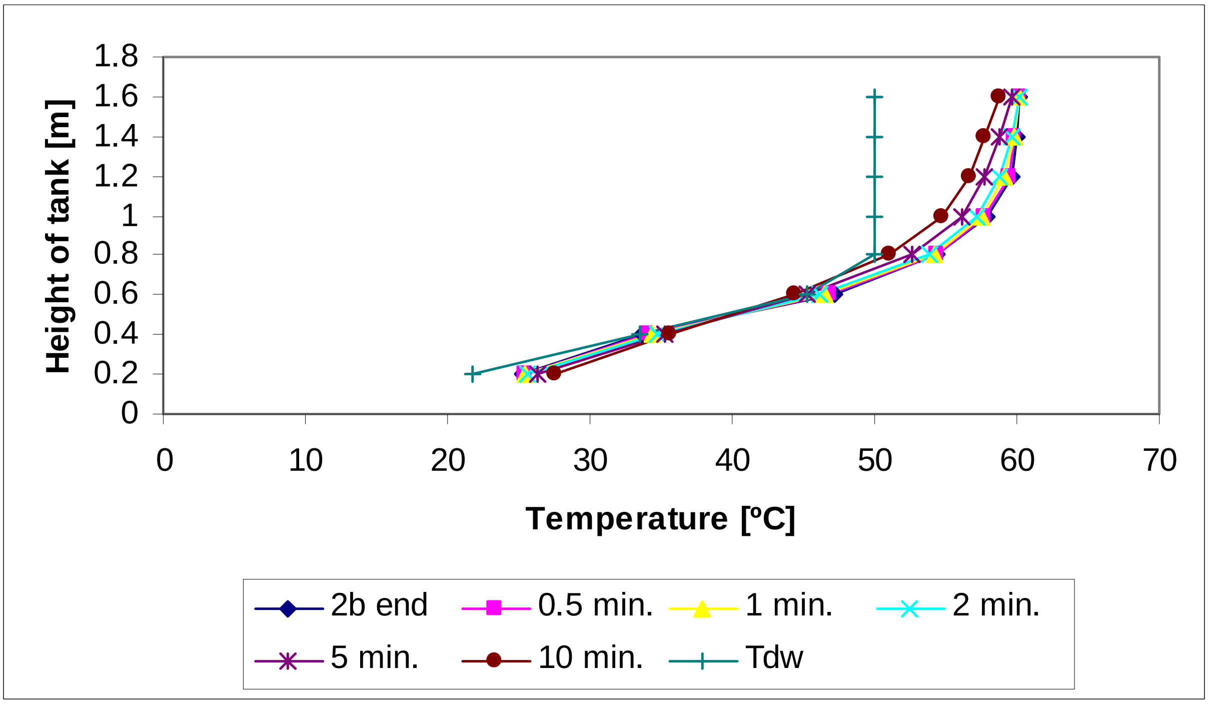

Figure 75: Calculated temperatures in the space heating storage tank after stop for boiler loop and space-heating loop after operation condition 2b.

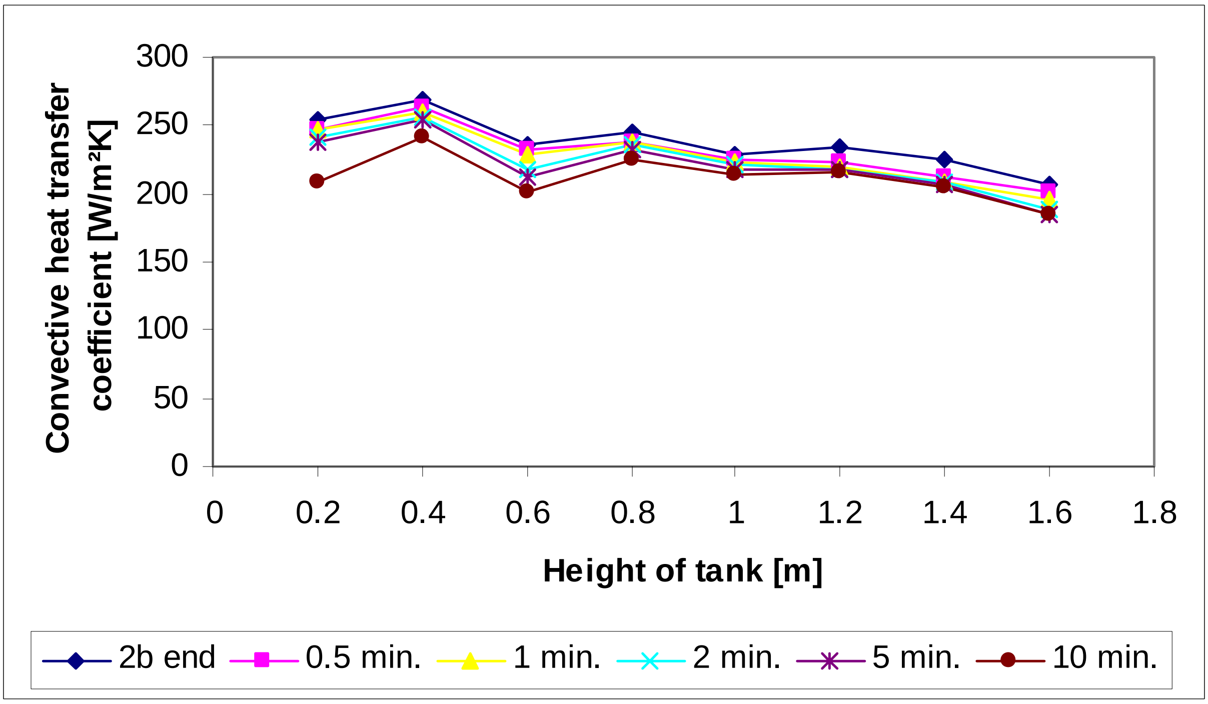

Figure 76: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall after stop for boiler loop and space-heating loop after operation condition 2b.

3.9 Summary and comparison of results

The results from the simulation of the single operation conditions have been treated in paragraphs 3.1 - 3.8. Below a summary of the results and a comparison between the single operation conditions will be given.

3.9.1 Thermal stratification

At operation conditions 1a-1c there was a large temperature difference between the outside of the hot-water tank and the water in the space heating storage tank at the start of the operation periods corresponding to a condition where a large quantity of domestic hot water had just been tapped.

At operation condition 1a only the boiler was in operation. The boiler loop had an inlet temperature to the space heating storage tank of 65ºC and the flow in the boiler loop was 10 l/min. At operation condition 1b both the boiler loop and the space-heating loop were in operation. The boiler loop had an inlet temperature to the space heating storage tank of 65ºC and the flow in the boiler loop was 10 l/min. The space-heating loop had an outlet temperature to the space heating storage tank of 20.5ºC and the flow in the space-heating loop was 0.7 l/min. At operation condition 1c both the boiler loop and the space-heating loop were in operation. The boiler loop had an inlet temperature to the space heating storage tank of 65ºC and the flow in the boiler loop was 10 l/min. The space-heating loop had an outlet temperature to the space heating storage tank of 20.5ºC and the flow in the space-heating loop was 1.4 l/min.

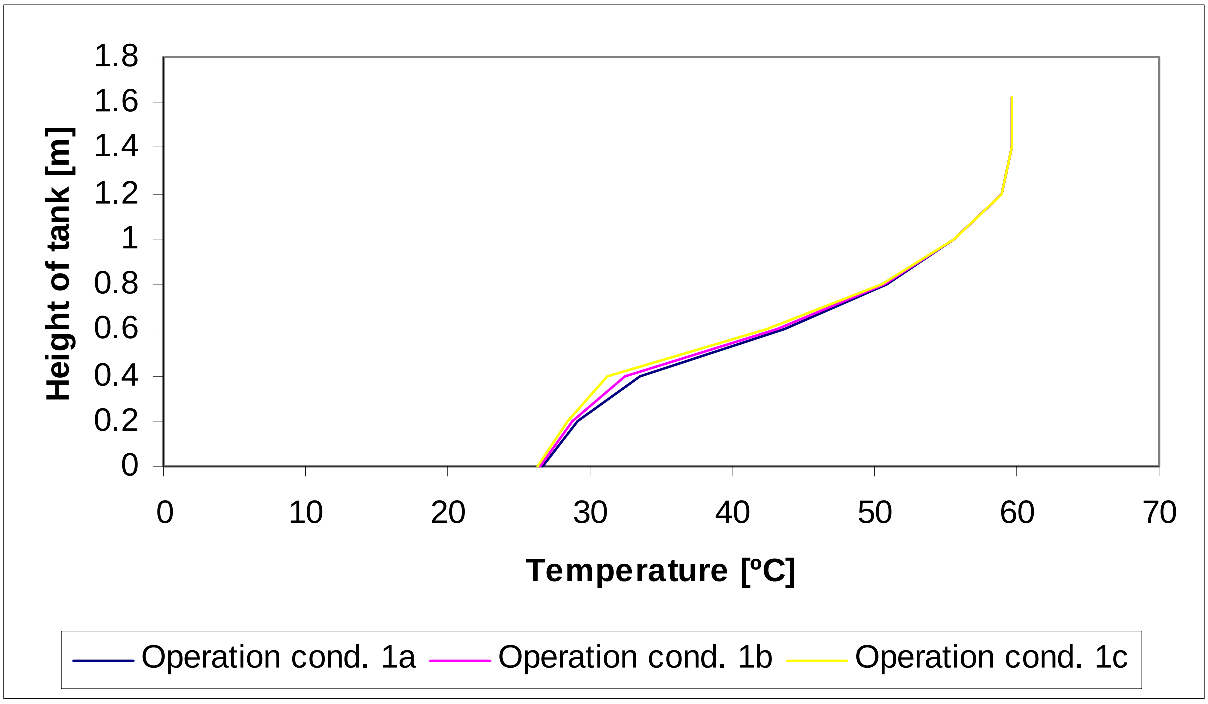

Figure 77: Thermal stratification in the space heating storage tank after 10 minutes in operation for operation condition 1a, 1b and 1c.

Figure 77 shows the thermal stratification in the space heating storage tank after simulation of 10 minutes in operation for operation conditions 1a, 1b, and 1c, respectively. It appears that there is a minimal difference in the temperature profiles for the three operation conditions, which shows that at these operation conditions it does not matter to the thermal stratification whether the space-heating loop is in operation or not.

At operation conditions 2a-2d there was a small temperature difference between the outside of the hot-water tank and the water in the space heating storage tank at the start of the operation periods indicating that both domestic water and space heating water was heated up.

At operation condition 2a, only the boiler was in operation. The boiler loop had an inlet temperature to the space heating storage tank of 65ºC and the flow in the boiler loop was 10 l/min. At operation condition 2b, both the boiler loop and the space-heating loop were in operation. The boiler loop had an inlet temperature to the space heating storage tank of 65ºC and the flow in the boiler loop was 10 l/min. The space-heating loop had an outlet temperature to the space heating storage tank of 20.5ºC and the flow in the space-heating loop was 1.4 l/min. At operation condition 2c, only the space-heating loop was in operation. The space-heating loop had an outlet temperature to the space heating storage tank of 20.5ºC and the flow in the space-heating loop was 1.4 l/min. At operation condition 2d, only the space-heating loop was in operation. The space-heating loop had an outlet temperature to the space heating storage tank of 30ºC and the flow in the space-heating loop was 1.4 l/min.

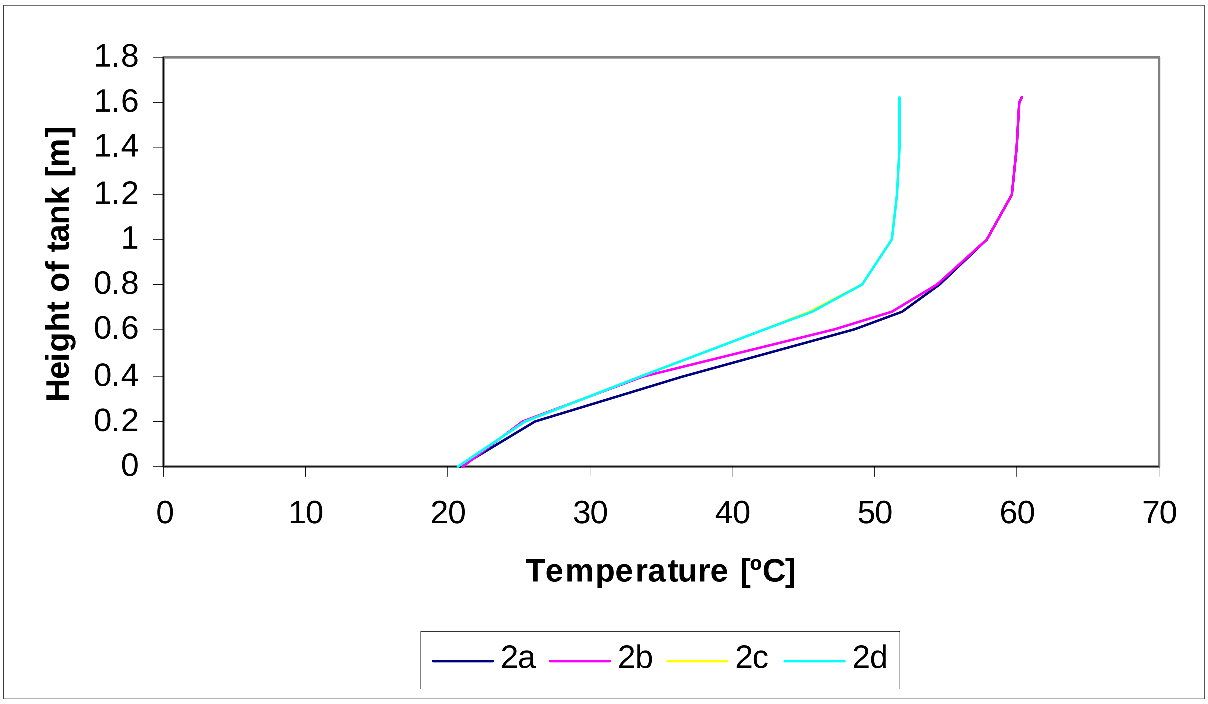

Figure 78: Thermal stratification in the space heating storage tank after 10 minutes in operation for operation condition 2a, 2b, 2c, and 2d.

Figure 78 shows the thermal stratification in the space heating storage tank after a simulation of 10 minutes in operation for operation conditions 2a, 2b, 2c, and 2d, respectively. The temperature profiles at operation conditions 2a and 2b, respectively, are very much the same. There is a small aberration around the inlet from the space-heating loop, which is due to the fact that the space-heating loop is in operation in operation condition 2b, unlike in operation condition 2a. The temperature profiles at operation condition 2c and 2d differ somewhat from the temperature profiles at operation conditions 2a and 2b, which is due to the fact that the boiler loop is not in operation either at operation condition 2c or 2d. On the other hand the temperature profiles are very much the same for operation conditions 2c and 2d. The difference between the two operation conditions is that the inlet temperature from the space-heating loop has been raised from 20.5ºC at operation condition 2c to 30º at operation condition 2d. The difference between the energy carried away to the space-heating loop is also just 0.15 kWh at the two operation conditions.

The analysis of the 7 operation conditions shows that the inlet from the space-heating loop does not give cause for any appreciable mixing, as the thermal stratification in the space heating storage tank does not change very much when the space-heating loop is in operation, compared to when it is not. There are, however, two circumstances that should be considered before drawing any conclusions about this. In the first place, the investigated operation conditions only take 10 minutes. 10 minutes are a comparatively long time with the boiler in operation, but it is a short period with the space-heating loop in operation. Therefore a longer operation period for the space-heating loop would perhaps result in greater mixing. The second circumstance that could have an influence on the results is that the temperature of the outside of the hot-water tank as a function of the height level is constant in the calculations so that it cannot change during the operation periods. This is not realistic, as the temperature will change as a result of the change of the temperature of the space heating water and by the heat transfer between the space heating water and the hot-water tank wall. In addition, low flows in the space-heating loop of 0.7 l/min and 1.4 l/min, respectively, have been used in the simulations. A larger flow would imply mixing, and in [1] experimental investigations have been carried out with a flow in the space-heating loop of 9 l/min in which there was a considerable mixing.

3.9.2 Fluid motion

Inlet from boiler loop:

The flows around the inlet from the boiler loop proved to be independent of the temperature differences between the inlet water and the water in the space heating storage tank on a level with the inlet. At all operation conditions where the boiler loop is in operation, the inlet flow enters and hits the tank wall against the domestic water and then flows horizontally, closely along the tank wall. There is a small recirculation on each side of the inlet flow. The flow is not completely symmetrical around the tank wall against the domestic water. This is due to the fact that the outlet to the boiler loop is turned 60º to the inlet from the boiler loop.

On the vertical level the water also flows in horizontally and hits the tank wall against the domestic water. From here some of the water flows down along the tank wall and most likely down towards the outlet to the boiler loop, whereas some of the water flows upwards along the tank wall towards the top of the tank. There is a downward flow along the tank wall against the domestic water in the side opposite the inlet from the boiler loop.

Outlet to boiler loop:

On a level with the outlet to the boiler loop, almost all the flow on the horizontal level has turned towards the outlet. However, it is only close to the outlet that the flow is of a certain extent, the rest of the flows are very small. Vertically, it is only close to the outlet that the outlet affects the flows.

Outlet to space-heating loop:
The flows around the outlet to the space-heating loop almost look like the flows on the level with the outlet to the boiler loop, still with the difference that the flow and thus the velocities in the space-heating loop are somewhat smaller. Furthermore, when the boiler loop is in operation there is a downward flow closely around the hot-water tank.

Inlet from space-heating loop:
The flow in the space-heating loop has not been particularly high at the investigated operation conditions. At the smallest flow of 0.7 l/min the cold inlet water flows quickly from the space-heating loop downwards in the space heating storage tank because of the temperature differences. At a flow of 1.4 l/min, the inlet flow gets a little further into the space heating storage tank before it flows downwards towards a lower temperature level. At a flow of 1.4 l/min and an inlet temperature of 30ºC (instead of 20.5ºC), the inlet flow gets even further into the space heating storage tank, a small part reaches right into the hot-water tank. The part flowing downwards in the tank does not get very far down, as the temperature of the flow is higher, and thus it reaches a suitable temperature level earlier.

3.9.3 Convective heat transfer coefficient for the outside of the hot-water tank

The convective heat transfer coefficient for the outside of the hot-water tank has been calculated by equation (2). Figure 79 shows the calculated convective heat transfer coefficients as a function of the height level in the tank for the operation conditions 1a, 1b, 1c, 2a, 2b, 2c, 2d and for the operation conditions 1d and 2e with stagnation in the space heating storage tank.

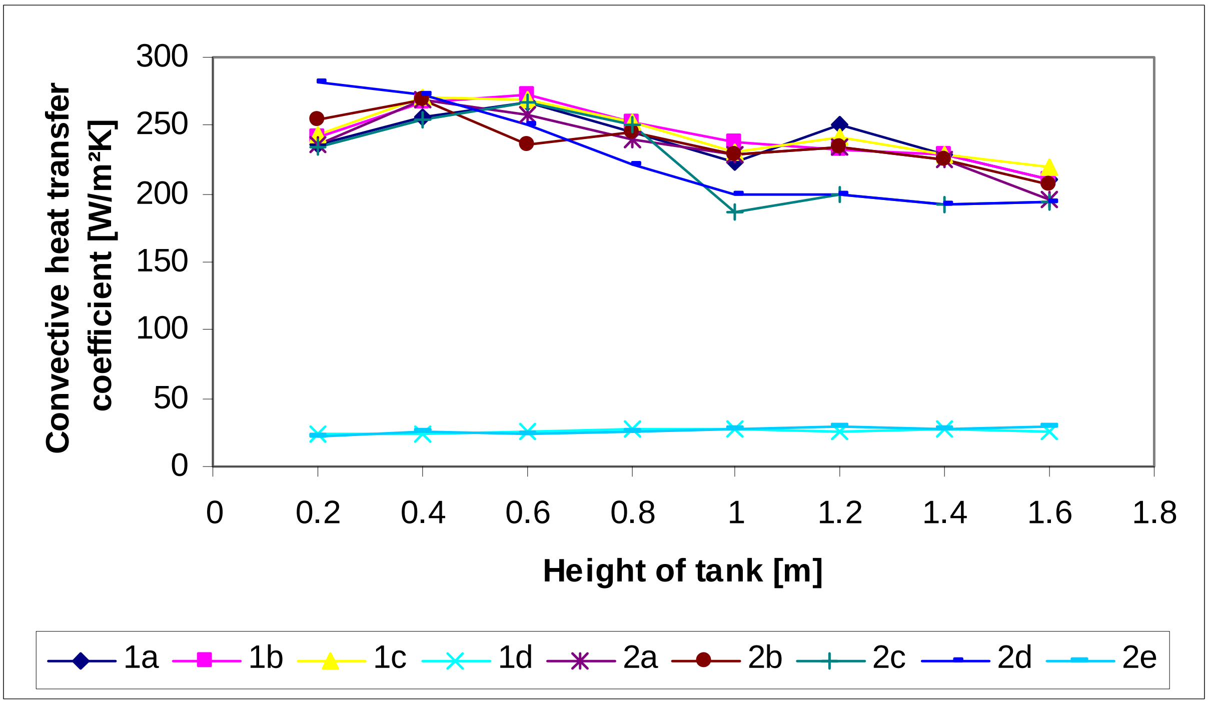

Figure 79: The calculated convective heat transfer coefficient for the outside of the hot-water tank wall as a function of the height at all the operation conditions. The convective heat transfer coefficient has been calculated by equation (2).

It appears from Figure 79 that there is no clear picture of the convective heat transfer coefficient at the different operation conditions. There are two things, however, that catch ones eye. The first thing is that the convective heat transfer coefficient for the top of the hot-water tank (over 1 m from the bottom) falls when the boiler loop is not in operation. The second thing is that the convective heat transfer coefficient falls drastically to about 25 W/m²·K when there is a stagnation in the space heating storage tank. However, the very low convective heat transfer coefficients only occur in cases where, by and large, there are no motions in the space heating storage tank. In periods shortly after the boiler loop and the space-heating loop have been in operation, the convective heat transfer coefficient is almost as great as when they are in operation. In these cases the convective heat transfer coefficient slowly decreases as the motions in the space heating storage tank decreases, which appears from Figure 72 and Figure 76.

In the light of Figure 79 the convective heat transfer coefficient for the outside of the hot-water tank wall can be drawn up op in the following way for the different operation conditions. The hot-water tank is divided into a lower part and an upper part. The lower part is the slim part of the hot-water tank from 0 m to 0.925 m where the tank expands. The upper part is where the hot-water tank has expanded from 0.925 m to 1.625 m, which is the top of the tank. Then the operation conditions have been divided into four categories: 1) only boiler in operation, 2) both boiler and space-heating loop in operation, 3) only space-heating loop in operation and 4) neither of them in operation. Table 6 shows the convective heat transfer coefficient at the four operation conditions.

	Convective heat transfer coefficient in upper part [W/m²·K]	Convective heat transfer coefficient in lower part [W/m²·K]
Only boiler in operation	196-250	236-269
Boiler and space-heating loop in operation	205-241	236-271
Only space-heating loop in operation	188-200	222-282
Neither of them in operation	26-29	23-27

Table 6: The convective heat transfer coefficient for the outside of the hot-water tank at four operation conditions. The ”lower part” of the hot-water tank is the lower slim part until the tank expands. The ”upper part” of the hot-water tank is from where it has expanded and to the top.

The combi store has been investigated experimentally in [1], and here the total convective heat transfer coefficient for the whole hot-water tank has been calculated to be between 200 W/K and 350 W/K. 200 W/K were calculated at low temperatures of about 18ºC in the space heating storage tank, whereas 350 W/K were calculated at high temperatures of about 53ºC in the space heating storage tank. Figure 80 shows an outline of the calculated average convective heat transfer coefficient for the outside of the hot-water tank at all operation conditions. Figure 81 shows an outline of the calculated total convective heat transfer coefficient for the outside of the hot-water tank at all operation conditions. It appears from Figure 81 that the total convective heat transfer coefficient for the outside of the hot-water tank at the operation conditions where there is motion in the space heating storage tank, is greater than the experimentally found convective heat transfer coefficient in [1]. This is owing to the fact that the calculated convective heat transfer coefficient only applies to the outside of the hot-water tank, whereas the experimentally found convective heat transfer coefficient is for heat transfer the whole way through the hot-water tank wall.

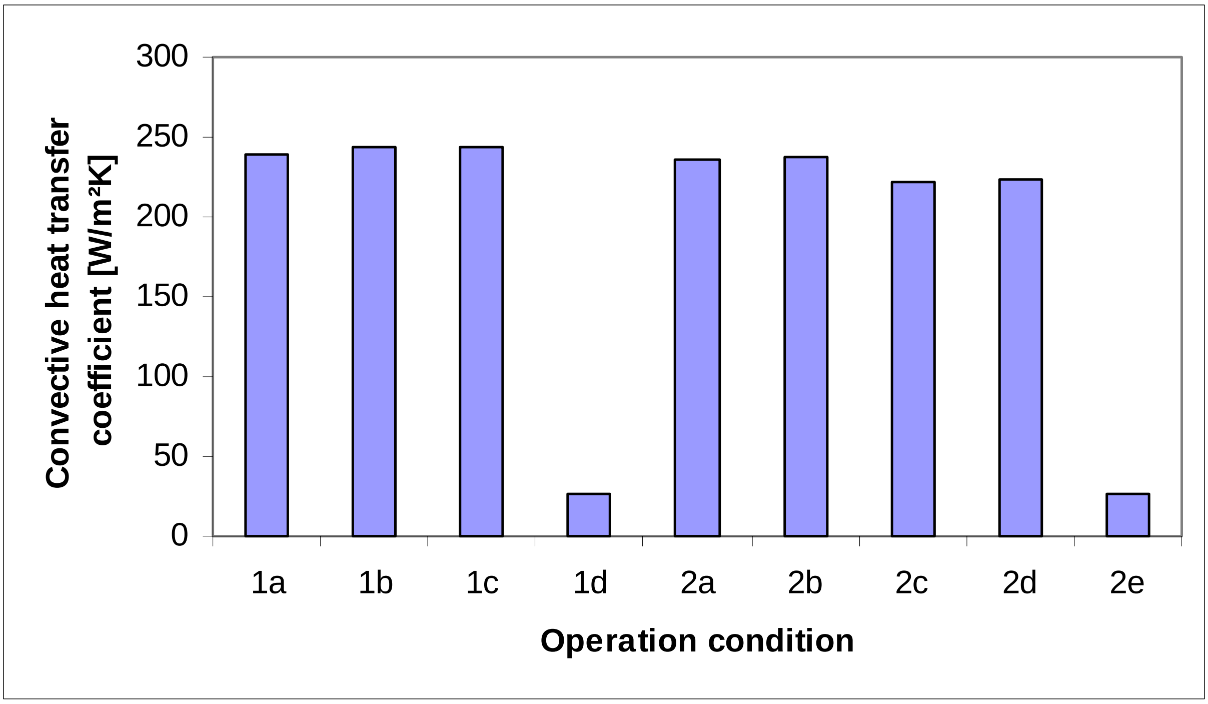

Figure 80: The calculated average convective heat transfer coefficient for the outside of the hot-water tank at all operation conditions.

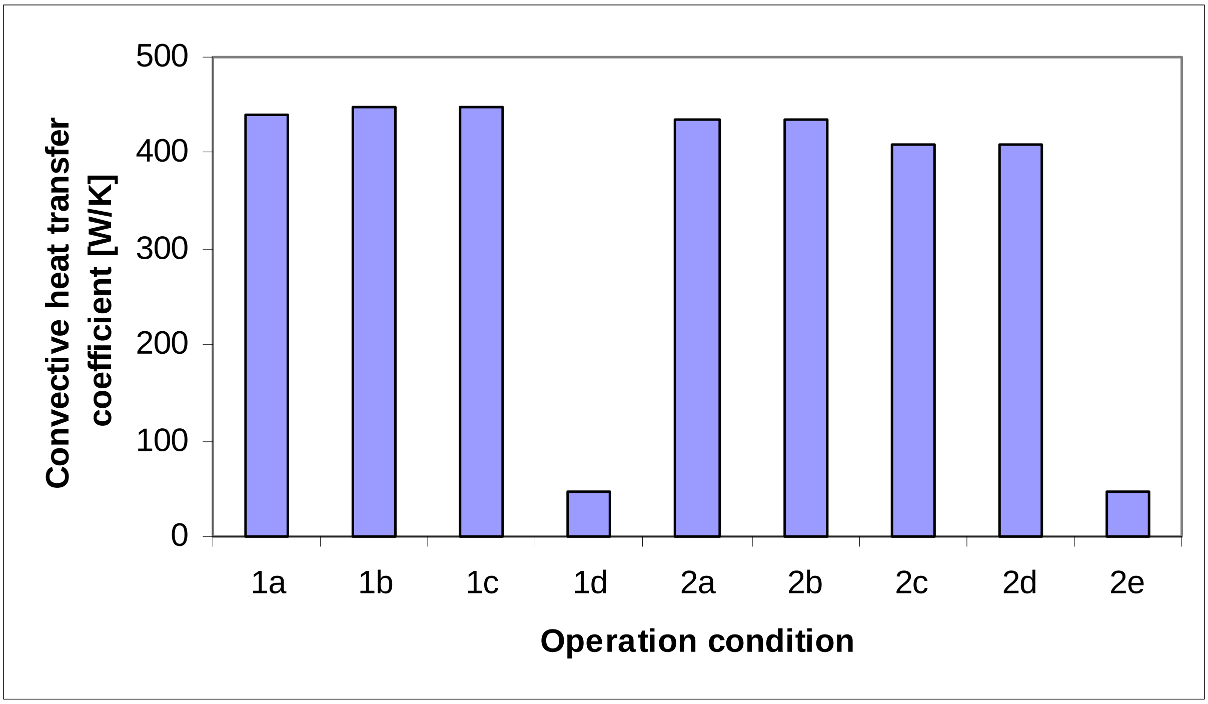

Figure 81: The calculated total convective heat transfer coefficient for the outside of the hot-water tank at al operation conditions.

4. Conclusion

Theoretical investigations of a heat storage for a solar combi system have been carried out. The investigated combi store has been manufactured by the Danish company Batec A/S. The theoretical investigations were carried out by means of a CFD-program, CFX 5.4.

A model of the combi store from Batec A/S has been built up in the CFD program. The model contains some simplifications compared to the real combi store. The CFD model does not include a solar heat exchanger, which means that only periods when the solar collector loop is not in operation can be simulated. Furthermore the domestic hot water is not included in the CFD model. Instead the tank wall of the DHW tank has a constant temperature during the simulation, and by this the heat transfer to the domestic water can be calculated.

The fluid motion and the thermal conditions in the combi store have been investigated during 7 different operation situations. The 7 operation conditions have been made up in such a way that situations are simulated where only the boiler loop is in operation, situations where both the boiler loop and the space-heating loop are in operation, and situations where only the space-heating loop is in operation. The conditions in the combi store have also been simulated under different temperature conditions.

The fluid motions around inlet from and outlet to boiler loop and space-heating loop in the space heating storage tank, respectively, have been investigated at the different operation conditions. The flows around outlet to boiler loop and space-heating loop, respectively, were very uniform. On a level with the outlet, almost all the flow had turned towards the outlet. However, it is only close to the outlet that the flow is of a certain extent. The rest of the horizontal flows on a level with the outlets are very small Vertically, it is only close to the outlet that the outlet affects the flows.

From the inlet of the boiler loop the water flows horizontally hitting the hot-water tank, after which it flows around it. On the vertical level some of the water flows downwards along the hot-water tank after having hit the tank and some flows upwards along the hot-water tank towards the top. At the inlet from the space-heating loop, the water flows quickly downwards in the space heating storage tank until it dies down in thermal equilibrium (at the investigated operation conditions the temperature of the water from the space-heating loop is lower than the temperature of the water in the space heating storage tank on the level with the inlet). In the investigated operation conditions the flow in the space-heating loop was 0.7 l/min and 1.4 l/min, respectively. At larger flows in the space-heating loop there is a risk that the inlet flow creates mixing and thus spoils the thermal stratification in the space heating storage tank. At the investigated operation conditions the operation of the space-heating loop had a minimal influence on the thermal stratification in the space heating storage tank.

At all the operation conditions the convective heat transfer coefficient for the outside of the hot-water tank wall has been calculated as a function of the height of the tank. The hot-water tank wall is divided into a lower part and an upper part, where the lower part is the slim part of the hot-water tank from 0 m to 0.925 m where the tank expands, and the upper part is where the hot-water tank has expanded from 0.925 m to 1.625 m. The convective heat transfer coefficient for the outside of the lower part of the hot-water tank wall was calculated to lie between 222 W/m^2K and 282 W/m^2K. For the upper part the convective heat transfer coefficient was calculated to lie between 196 W/m^2K and 250 W/m^2K when the boiler is in operation. When the boiler is not in operation the convective heat transfer coefficient for the upper part of the outside of the hot-water tank wall is calculated to lie between 188 W/m²K and 200 W/m²K. When neither boiler loop nor space-heating loop is in operation, and when by and large no motion of the water occurs in the space heating storage tank the convective heat transfer coefficient for den lower part lies between 23 W/m²K and 27 W/m²K, whereas the convective heat transfer coefficient for the upper part lies between 26 W/m²K and 29 W/m²K.

In terms of thermal performance the heat storage is the most important part of a solar heating system. It is therefore important to predict the characteristics of the heat storage at different operation conditions in order to be able to make the best possible design of the heat storage. The operation of the system during a year can be simulated by means of models that are simpler than CFD-models. Some of the results from the CFD-calculations in this project can be implemented in the simpler models so they can be as accurate as possible. If the calculated convective heat transfer coefficients for the outside of the hot-water tank are implemented in a simpler simulation program it is possible to describe the heat transfer between the space-heating water and the wall of the hot-water tank. However, in order to describe the heat transfer between the wall of the hot-water tank and the domestic water it is necessary with additional CFD-calculations, but this is not part of the current project.

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